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THE DEPARTMENT OF DEFENSE

CRITICAL TECHNOLOGIES PLAN

FOR THE
COMMITTEES ON ARMED SERVICES
UNITED STATES CONGRESS

15 MARCH 1989
REVISED 5 MAY 1989

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19. ABSTRACT (Continue on reverse if necessary and identify by block number) THIS IS A REVISION OF THE REPORT OF THE SAME TITLE DATED 15 MARCH 1989, RESPONDING TO PUBLIC LAW 100-456, THE NATIONAL DEFENSE AUTHORIZATION ACT FOR FISCAL YEAR 1989, TO PROVIDE CONGRESS ANNUALLY WITH A CRITICAL TECHNOLOGIES PLAN. IT IS THE RESULT OF A SERIES OF MEETINGS INVOLVING REPRESENTATIVES OF THE MILITARY DEPARTMENTS AND DEFENSE AGENCIES WITH RESPONSIBILITIES FOR SCIENCE AND TECHNOLOGY PROGRAMS, AND REPRESENTATIVES FROM THE DEPARTMENT OF ENERGY, ASSISTANT SECRETARY FOR DEFENSE PROGRAMS. AFTER DEFINING THE SCOPE OF THE REPORT AND OUTLINING THE DOD PLANNING PROCESS FOR SCIENCE AND TECHNOLOGY, SELECTION CRITERIA FOR CRITICAL TECHNOLOGIES ARE PRESENTED. TECHNOLOGIES RELATED TO NUCLEAR WEAPONS AND THEIR EFFECTS, BECAUSE OF THEIR SPECIAL NATURE, ARE NOT INCLUDED IN THIS PLAN. CRITICAL TECHNOLOGIES ARE TECHNOLOGIES WITH GREAT PROMISE OF ENSURING THE LONG-TERM SUPERIORITY OF UNITED STATES WEAPON SYSTEMS. THE FOLLOWING CRITICAL TECHNOLOGIES WERE SELECTED: MICROELECTRONIC CIRCUITS AND THEIR FABRICATION; PREPARATION OF GAAS AND OTHER COMPOUND SEMI-CONDUCTORS; SOFTWARE PRODUCIBILITY; (OVER)

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(R&AT) 17 JUL 1989

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Request that you remove document ADA206130. Department of Defense Critical Technologies Plan for the Committees on Armed Services United States Congress, dated 15 March 1989, from the DROLS database.

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Leo Young

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Staff Specialist, Logistics R&D

THE DEPARTMENT OF DEFENSE

CRITICAL TECHNOLOGIES PLAN

FOR THE
COMMITTEES ON ARMED SERVICES
UNITED STATES CONGRESS

15 MARCH 1989
REVISED 5 MAY 1989

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EXECUTIVE SUMMARY

Congressional Requirement

The report responds to Public Law 100-456, the National Defense Authorization Act for Fiscal Year 1989, to provide Congress annually with a Critical Technologies Plan. This is the first such submission. It is the result of a series of meetings involving representatives of the military departments and defense agencies with responsibilities for science and technology programs, and representatives from the Department of Energy, Assistant Secretary for Defense Programs.

Critical Technologies

After defining the scope of the report and outlining the DoD planning process for science and technology, selection criteria for critical technologies are presented. Technologies related to nuclear weapons and their effects, because of their special nature, are not included in this plan. Critical technologies are technologies with great promise of ensuring the long-term superiority of United States weapon systems. However, that promise can be realized only when they are integrated into *a balanced science and technology program* with a full spectrum of mutually supportive technologies.

The following critical technologies were selected:

- Microelectronic Circuits and Their Fabrication
- Preparation of GaAs and Other Compound Semi-Conductors
- Software Producibility
- Parallel Computer Architectures
- Machine Intelligence/Robotics
- Simulation and Modeling
- Integrated Optics
- Fiber Optics
- Sensitive Radars

- Passive Sensors
- Automatic Target Recognition
- Phased Arrays
- Data Fusion
- Signature Control
- Computational Fluid Dynamics
- Air Breathing Propulsion
- High Power Microwaves
- Pulsed Power
- Hypervelocity Projectiles
- High-Temperature/High-Strength/Light-Weight Composite Materials
- Superconductivity
- Biotechnology Materials and Processing.

This list of critical technologies should not be regarded as a closed list. Other important technologies may become prime candidates for another year's list.

The application of critical technologies to products and processes is displayed by means of a table. Major national efforts in other countries are summarized. A short account of each technology is appended, including a summary description, its impact on weapons systems, planned R&D in Defense, and related programs in the United States and in other countries.

Science and Technology (S&T) Investment Strategy

The relationship between the Critical Technologies Plan and the DoD science and technology (S&T) investment strategy is discussed. They share the same objectives, namely technology planning to meet defense needs. However, whereas the Critical Technologies Plan is to select the star performers, the S&T investment strategy must take into account the whole team. This strategy depends on a balanced S&T program in which the critical technologies play a highly visible but not the only important role. The list must not be confused with a budget proposal. Stability in funding and perseverance are crucial to ensure yearly improvements, which when compounded can have a dramatic effect in the long run.

CRITICAL TECHNOLOGIES PLAN

A. PURPOSE

This report responds to Public Law 100-456, the National Defense Authorization Act, Fiscal Year 1989, of 29 September 1988, which requires that the Department of Defense (DoD) submit annually, and not later than March 15 of each year, a CRITICAL TECHNOLOGIES PLAN, the first such plan to be submitted in Calendar Year 1989. The full statement of Section 823, PL 100-456, is reproduced in Appendix B. The report is the result of a series of meetings involving representatives of the military departments and defense agencies with responsibilities for science and technology programs, and representatives from the Department of Energy, Assistant Secretary for Defense Programs.

Numerous reports have been written in recent years on technologies termed the "most important," or "key," or "emerging," or "critical," etc., having different purposes and applications, as for example, for export control of technological "know-how," for net assessment of foreign technological capabilities or deployment, for competitive strategies, for investment purposes, and so on. It was therefore considered necessary to limit the scope in a purposeful way, and to provide a uniform rationale for selecting "critical technologies" in consonance with the description in PL 100-456, namely as "the technologies most essential to develop in order to ensure the long-term qualitative superiority of United States weapon systems."

The purpose of this report is to select and provide background information on the critical technologies. This will be done within the larger context of a DoD science and technology (S&T) investment strategy.

B. BACKGROUND

1. Scope

The term "technology" has many meanings. In DoD, the term can be applied to mission-oriented themes (such as Guidance and Control Technology) or to specific topics in manufacturing (such as electron beam lithography). Still other uses of the term can be found.

For this report, the best definition of the term technology is "*the science of* the application of knowledge to practical purposes." Therefore, we have defined our critical technologies largely in terms of specific scientific topics as opposed to mission-oriented titles (such as Guidance and Control Technology). The terminology used in this report thus enables science and technology managers to discriminate between the specific choices they are best qualified to make.

Working with this definition, the critical technologies are found principally within the DoD science and technology (S&T) program under budget categories 6.1 (research), 6.2 (exploratory development), and 6.3A (advanced technology development). Note that fabrication processes are addressed in each critical technology (e.g., Microelectronics, Software, Robotics, Modeling, Sensors, etc.). Technologies related to nuclear weapons and nuclear weapon effects, because of their special nature, are not included in this plan.

Some selected "critical technologies" may come with high potential reward but also high risk. In the conceptual (6.1) stage for these technologies, it may pay to follow several alternative approaches, rather than to restrict efforts to only one approach. The proof-of-feasibility (6.2) stage often identifies the most promising of these approaches and thus narrows the future development options, while the demonstration (6.3A) stage of development is intended to bring a particular approach to the point of transitioning into a system. As development advances, costs usually escalate and hard choices among approaches must be made. This forecloses the remaining less promising technology alternatives.

2. The Planning Process for Science and Technology

The DoD S&T planning process is an iterative, interactive process in which technology managers choose between many alternative and competing technologies in order to respond to guidance from military planners and policy makers.

DoD must be capable of response throughout the spectrum of conflict from terrorist action to global conflict. Thus, current national defense deficiencies in warfighting capabilities as well as changing threat projections largely determine the elements of the DoD science and technology program.

To this end, the Office of the Secretary of Defense (OSD) conducts a top-down and bottom-up interactive strategic planning process for science and technology. In this planning process, the Military Services and Defense Agencies work with OSD to develop investment strategies that are responsive to the defense guidance.

An overview of this process is shown in Figure 1. It ensures creation of a strong S&T program that will maintain technological superiority in our warfighting capability. The process also provides an annual update of the critical technologies plan.

DoD regularly reviews its investment strategy for technology. For example, the Defense Science Board (DSB) undertook a special study of the management of the DoD S&T program in the summer of 1987. The DSB conducts several evaluations of technology issues every year. Furthermore, in-depth reviews of the DoD technology investment strategy are held annually (most recently in September 1988) by senior representatives from OSD, the Military Services, and the Defense Agencies. These reviews address the full spectrum of technology issues The DoD planning process makes S&T investment activities more visible to both planners and users. This Critical Technologies Plan has the same basic objectives as the investment strategy, and is a natural output of the existing DoD planning process.

There is, however, an important distinction between the Critical Technologies Plan and the S&T investment strategy. Whereas the former focuses only on the star performers on the team (the technologies projected to make the most noticeable difference), the latter takes into account *all* considerations, without which the team could not perform effectively. Steadily improving technologies are an essential part of the overall S&T investment strategy and must not be shortchanged when recognizing the more visible role of the "critical technologies."

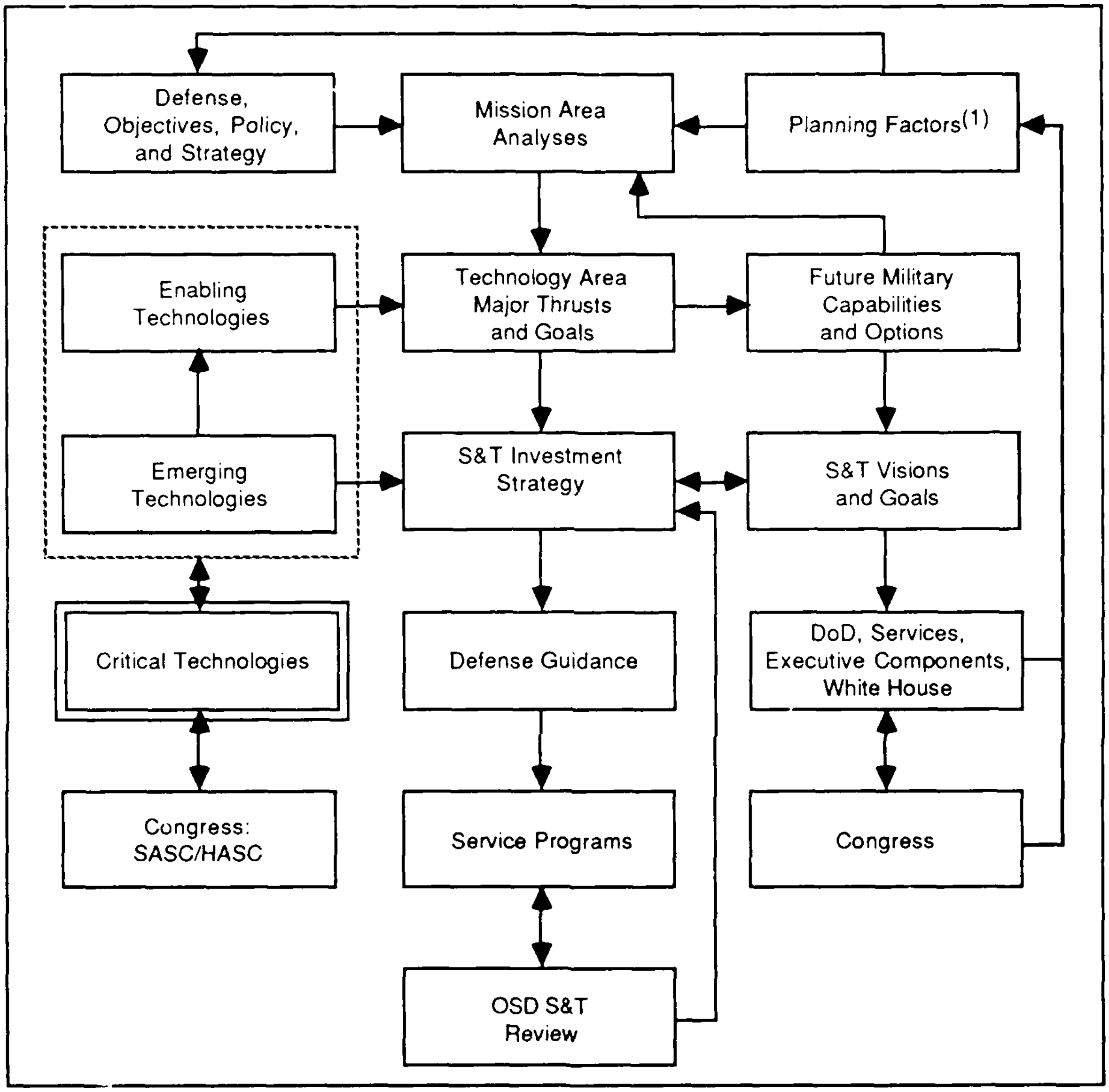

Figure 1. DoD Science and Technology (S&T) Strategic Planning Process[2]

Notes with Figure 1:

(1) Planning Factors include the world situation, budget constraints, Presidential guidance, Congressional mandates, etc.

(2) This block diagram cannot show all the many interactions that take place informally.

C. CRITICAL TECHNOLOGIES

1. Rationale for Selecting Critical Technologies

For the purposes of this report, critical technologies are selected on the basis of one or more of the Performance and Quality Design criteria listed below:

Performance Criteria

1. Technologies that enhance performance of conventional weapons systems
2. Technologies that provide new military capabilities

Quality Design Criteria

3. Technologies that improve weapon systems availability and dependability
4. Technologies that improve weapon systems affordability.

To qualify as "critical," the technology improvements should be significant and quantifiable. A significant improvement embodies one or more of these performance or quality criteria when improved, for example, by a factor of about three.

The criteria above are not necessarily independent, nor are they the only criteria to be taken into consideration. A Sputnik-like surprise, or an unexpected surge in terrorist activity, could affect the technologies selected. Thus, DoD's selection process is a dynamic one which requires constant attention and sometimes rapid re-evaluation in light of technology breakthroughs or new operational demands. The evaluation process must recognize the changing fiscal environment as well as the need to ensure that the user gets the most cost effective product.

2. Selection of Critical Technologies

The critical technologies selected and shown in this section are discussed in detail in Appendix A, where the specific questions raised in PL 100-456 (reproduced in Appendix B) are addressed. The critical technologies often represent examples of cutting-edge technologies embedded in the larger technology areas. These larger technology areas in turn contain important technologies which may themselves become excellent candidates for a future year's Critical Technologies Plan.

This Plan is about the technologies most essential to ensure the superiority of our weapon systems. However, no weapon in the hands of a soldier or sailor or airman who is

poorly trained will achieve its superior potential. Therefore, technologies that result in better training are candidates for critical technologies (e.g., Simulation and Modeling). Similarly, with technologies dealing with preventive medicine, since a sick or disabled or dead soldier will not get the most out of his weapon. (There was no vaccine to stem the 1918 flu epidemic, which felled more soldiers than died from combat in World War I.)

A technology absent from the list must not automatically be regarded as "not important." For example, the oceans are critical to the Navy and to the nation; the selection of acoustic-array sites based on a knowledge of the ocean floor can vastly affect the ability to detect submarines. Ducting over the ocean surface can multiply the radar range for surface ship detection. These technologies could have been listed as critical, as could others relating to the environment. Technologies to *protect* against superior weapons such as high-energy laser beams or high-power microwaves, as well as against chemical and biological warfare, although not specifically listed, may also be considered critical.

Thus no such list can be considered as complete or comprehensive. Our list is presented in Table 1 with a brief statement of objectives. Table 2 indicates the important role these technologies play in improving products as well as processes for defense needs.

D. A BALANCED S&T PROGRAM

1. Need for Balance

An effective S&T program, like an effective team, must be well balanced. For example, superior future weapon systems should have superior simulators to train their crews. Engine improvements require an integrated balanced program advancing the state of the art in more than one technology, from fluid dynamics to high temperature materials. An effective program is a *well balanced* program.

Disproportionate funding for a particular "critical technology" taken out of context, without matching increases for related technologies, is not a good national strategy. Therefore, this list must not be confused with a budget proposal. The technologies identified herein are *some* of the technologies most essential for the long-term qualitative superiority of US weapon systems, but do not constitute a *complete* list of important and supporting technologies. A degree of subjectivity is almost bound to exist in any such selection process.

Table 1. List of Critical Technologies and Their Objectives

Critical Technology	Objective
1. Microelectronics Circuits and Their Fabrication	The production of ultra-small integrated electronic devices for high-speed computers, sensitive receivers, automatic control, etc.
2. Preparation of Gallium Arsenide (GaAs) and Other Compound Semi-Conductors	The preparation of high purity GaAs and other compound semi-conductor substrates and thin films for microelectronic substrates.
3. Software Producibility	The generation of affordable and reliable software in timely fashion.
4. Parallel Computer Architectures	Ultra-high-speed computing by simultaneous use of all processing capabilities in the next generation of computers.
5. Machine Intelligence/Robotics	Incorporation of human "intelligence" and actions into mechanical devices.
6. Simulation and Modeling	Testing of concepts and designs without building physical replicas.
7. Integrated Optics	Optical memories and optical signal and data processing.
8. Fiber Optics	Ultra low loss fibers and optical components such as switches, couplers, and multiplexers for communictions, navigation, etc.
9. Sensitive Radars	Radar sensors capable of detecting low-observable targets, and/or capable of non-cooperative target classification, recognition, and/or identification.
10. Passive Sensors	Sensors not needing to emit signals (hence passive) to detect targets, monitor the environment, or determine the status or condition of equipment.
11. Automatic Target Recognition	Combination of computer architecture, algorithms, and signal processing for near real-time automation of detection, classification, and tracking of targets.
12. Phased Arrays	Formation of spatial beams by controlling the phase and amplitude of RF signals at individual sensor elements distributed along an array (radar, underwater acoustic, or other).
13. Data Fusion	The machine integration and/or interpretation of data and its presentation in convenient form to the human operator.
14. Signature Control	The ability to control the target signature (radar, optical, acoustic, or other) and thereby enhance the survivability of vehicles and weapon systems.
15. Computational Fluid Dynamics	The modeling of complex fluid flow to make dependable predictions by computing, thus saving time and money previously required for expensive facilities and experiments.
16. Air Breathing Propulsion	Light-weight, fuel efficient engines using atmospheric oxygen to support combustion.
17. High Power Microwaves	Microwave radiation at high power levels for weapon applications to temporarily or permanently disable sensors, or to do structural damage.
18. Pulsed Power	The generation of power in the field with relatively light-weight, low-volume devices.
19. Hypervelocity Projectiles	The generation and use of hypervelocity projectiles to (1) penetrate hardened targets, and (2) increase the weapon's effective range.
20. High-Temperature/High-Strength/ Light-Weight Composite Materials	Materials possessing high strength, low weight, and/or able to withstand high temperatures for aerospace and other applications.
21. Superconductivity	The fabrication and exploitation of superconducting materials.
22. Biotechnology Materials and Processing	The systematic application of biology for an end use in military engineering or medicine.

Table 2. Critical Technologies Versus Products and Processes

Applications to Products and Processes / Critical Technologies	Weapons					Platforms				Information Systems						Support							
	Smart Weapons	Ballistic Missiles	BMD/ASAT	Electronic Combat	Electromag Weapons	Tanks/Ground Vehicles	Submarines/Ships	Aircraft	Spacecraft	Search & Surveillance	Reconnaissance	Battle Mgmt/C3	Non-Cooperative ID	Guidance & Control	Arms Control	Design & Integration	Manufacturing	Maintenance/Logistics	Test & Evaluation	Training	CBD	Medical	Combat Environment
1. Microelectronic Circuits and Their Fabrication	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
2. Preparation of GaAs and Other Compound Semi-Conductors	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
3. Software Producibility	X	X	X	X						X	X	X	X	X	X	X	X		X	X	X		X
4. Parallel Computer Architectures		X	X	X						X	X	X	X		X			X	X			X	X
5. Machine Intelligence/ Robotics	X	X	X	X		X	X	X		X	X	X	X	X	X	X	X	X	X	X	X		X
6. Simulation and Modeling	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
7. Integrated Optics	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X						
8. Fiber Optics						X	X	X	X	X	X	X				X	X	X					
9. Sensitive Radars	X		X	X	X					X	X		X		X	X	X				X	X	X
10. Passive Sensors	X	X	X	X		X	X	X		X	X		X	X	X	X	X	X			X	X	X
11. Automatic Target Recognition	X	X	X							X	X	X	X	X	X	X							X
12. Phased Arrays	X	X	X	X						X	X	X	X		X	X	X						
13. Data Fusion	X		X	X		X	X	X	X	X	X	X	X	X	X	X			X	X			X
14. Signature Control				X		X	X	X	X	X	X	X	X			X							X
15. Computational Fluid Dynamics						X	X	X	X							X			X				
16. Air Breathing Propulsion	X		X			X		X								X	X						
17. High Power Microwaves					X					X	X	X				X	X						
18. Pulsed Power			X		X	X	X	X	X														
19. Hypervelocity Projectiles			X		X																		
20. High-Temp/High-Strength/ Light-Weight Composite Materials	X	X	X	X	X	X	X	X	X							X	X	X					
21. Superconductivity	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X						
22. Biotechnology Materials and Processing																X	X				X	X	

2. Technology and the Industrial Base

Recognizing that both *quality* and *quantity* are necessary to make an effective and powerful force, technologies must be developed to address *total* capability--quality (performance) *and* quantity (cost). In the past, DoD has depended on competition to obtain lowest cost, leaving production know-how and strategy to industry. As commercial production moved increasingly off-shore, US defense contractors began to lose the competitive edge in many commercial products similar to ones also incorporated into defense systems, thus weakening defense production.

DoD has become more and more concerned about the US industrial base. Various initiatives have been undertaken to help restore the competitiveness of US industry. It is beyond the scope of this report to describe all these initiatives, but it is important to consider how the science and technology program (budget categories 6.1, 6.2, and 6.3A) enhances our capability to apply technological advances to both products and processes. Examples can be found throughout this report.

The need to integrate technologies into systems (products) also has been recognized for a long time. The need to integrate technologies into functions (processes such as manufacturing and logistics) is equally important. Such efforts are being pursued vigorously by DoD through numerous advanced technology demonstration programs.

E. OVERALL ASSESSMENT

Because of the increasing dependency of modern weapon systems on high technology, the DoD science and technology program remains in the forefront for development and application of new technologies. From the genesis of radar and nuclear power in World War II to the origins of the aerospace, electronics, and computer industries in more recent years, defense requirements have resulted in previously unimagined new commercial products, and sometimes entirely new industries. Current DoD programs emphasize the direct support of R&D in universities and industry and are coordinated with independent R&D in industry to speed the transition from research to practical use.

Major efforts in technology exist in many countries. Concerning our principal allies and potential adversaries and some other countries, Table 3 provides a summary net assessment in these 22 critical technologies. Detailed narrative assessments an each technology will be found in Appendix A. The United States continues to maintain a world lead in these critical technologies, but there exist key niches of technology where other countries are aggressively moving ahead, and have matched or surpassed our capabilities. In Appendix A a number of such areas with potential for constructive cooperation are identified.

> *Japan*: In key niches of microelectronics, optics, superconductivity, and information systems technologies, Japan either holds or shares a worldwide lead. Japan has shown a growing interest in and willingness to expand its military technology base. Japan could play a major role in future cooperative arms developments.
>
> *NATO*: Our allies have strong national programs, and are closing gaps in some significant aspect of every critical technology. There are, therefore, numerous opportunities for cooperation in niche technologies. Progress towards true European unification in 1992, coupled with agressive multinational efforts in information technology, materials, and military systems will further enhance NATO capability.

F. PLANNING FOR THE FUTURE

DoD's strategic planning process helps identify and revise the list of critical technologies. In addition to identifying and funding the critical technologies, DoD continues to examine, program, fund, and execute a balanced S&T program that provides the greatest potential payback for investment. The Critical Technologies Plan does not endorse one technology over another, but does identify the "star" performers in a larger team of all-important technologies.

Evolutionary developments and steady progress are as important as technological breakthroughs. The effect of "compound yearly improvements" can be dramatic over a long period of time. Stability in funding and perseverance pay off. Uncertainty in funding makes planning difficult and execution inefficient and is detrimental to progress.

Table 3. Summary of Foreign Technological Capabilities

Critical Technologies	Warsaw Pact	NATO Allies	Japan	Others
1. Microelectronic Circuits and Their Fabrication	■	▨▨	▨▨▨▨	▨▨ Israel; ▨ S. Korea
2. Preparation of GaAs and Other Compound Semiconductors	■	▨▨	▨▨▨▨	
3. Software Producibility	■	▨▨	▨▨	▨▨ Many Nations
4. Parallel Computer Architectures	■	▨▨	▨▨	
5. Machine Intelligence/Robotics	■	▨▨▨	▨▨▨▨	▨▨ Finland, Sweden
6. Simulation and Modeling	■	▨▨	▨▨	
7. Integrated Optics	■■	▨▨▨	▨▨▨▨	▨ China, Israel, S. Korea
8. Fiber Optics	■	▨▨	▨▨▨	▨ Various Sources
9. Sensitive Radars	■	▨▨	▨▨	▨▨ Sweden
10. Passive Sensors	■■	▨▨	▨▨	▨ Israel
11. Automatic Target Recognition	■■	▨▨	▨▨	▨▨ Israel, Sweden
12. Phased Arrays	■	▨▨	▨	▨ Israel
13. Data Fusion	■■	▨▨	▨▨	
14. Signature Control	■	▨▨	NA	
15. Computational Fluid Dynamics	■	▨▨	▨▨	▨▨ Sweden
16. Air-Breathing Propulsion	■■	▨▨▨	▨▨	
17. High Power Microwaves	■■■■	▨▨		
18. Pulsed Power	■■■■	▨▨	▨▨	
19. Hypervelocity Projectiles	■■■	▨▨	▨▨	▨ Australia, Israel
20. High-Temperature/High-Strength/Low-Weight Composite Materials	■■	▨▨▨	▨▨▨	
21. Superconductivity	■■	▨▨	▨▨▨▨	
22. Biotechnology Materials and Processing	■■	▨▨▨	▨▨▨▨	▨▨ Many Nations

LEGEND:

Position of Warsaw Pact relative to the United States

- ■■■■ significant leads in some niches of technology
- ■■■ generally on a par with the United States
- ■■ generally lagging except in some areas
- ■ lagging in all important aspects

Capability of allies to contribute to the technology

- ▨▨▨▨ significantly ahead in some niches of technology
- ▨▨▨ capable of making major contributions
- ▨▨ capable of making some contributions
- ▨ unlikely to make any immediate contribution

Appendix A

ANALYSES OF CRITICAL TECHNOLOGIES

INDEX OF CRITICAL TECHNOLOGIES

INTRODUCTION

This appendix provides a detailed analysis of each critical technology area using the following structure:

A. SUMMARY DESCRIPTION

-- a one- or two-page paragraph overview description of the designated technology area.

B. IMPACT ON US WEAPONS

-- a description of the improved performance offered by the new technology and an evaluation of its potential value to future weapon systems, classes of systems, or support functions. Tables of goals and payoffs are provided where appropriate.

C. PLANNED R&D

-- a description of current DoD funded projects to develop and apply this technology. Milestone tables showing specific technology thrusts and projected completion dates are included. An estimate of the FY 1990 funding for this technology area is also provided. Generally this embraces a great many individual projects.

D. RELATED R&D IN THE UNITED STATES

-- a brief summary of related R&D performed by other government agencies, by academic institutions and by industry, including both IR&D and commercial research.

E. COMPARISON WITH OTHER COUNTRIES

-- an assessment of the state of development of this technology area in other countries, including our NATO allies, Japan, other developing countries, and the Warsaw Pact. A major purpose of this comparison is to identify countries that are viable candidates to contribute to international cooperative arms

developments. A country is, therefore, listed only if there is compelling evidence that it possesses at least some of the following characteristics:

(1) *A substantial infrastructure and national commitment.* This may be evidenced by national programs, including government-supported facilities and research. There should be a significant national investment and commitment to the technology infrastructure in intellectual, fiscal, and physical terms.

(2) *Specific areas of excellence.* Even in cases where the overall infrastructure in an area lags severely, there may be specific niches of R&D excellence capable of contributing to the advancement of the field.

It should be noted that the present comparison differs from previous net assessments in that the focus has shifted from comparing "averages" to looking for significant niche technologies indicating present or future strengths in adversaries, or offering opportunities of cooperation for common benefit to the US and its allies. This approach was taken to better meet the intent of the Congressional language.

1. MICROELECTRONIC CIRCUITS AND THEIR FABRICATION

A. SUMMARY DESCRIPTION

Microelectronics technology encompasses a range of fabrication technologies used to manufacture miniaturized electronic devices mainly on silicon or gallium arsenide substrates. The components of microelectronics fabrication technology may be divided into the following categories:

Wafer Preparation: The technology used for mass-production quality semiconductor wafers, including crystal growers, slicers, polishers, and preliminary dopant equipment.

Wafer Fabrication: The body of technologies used to fabricate integrated circuits on the prepared wafers, including lithography systems, ion-implantation machinery, thin film deposition and removal technology, clean room technology, etc.

Mask Making and Design: The "off-line" technology used to make "camera ready" circuit masks (used by lithography and doping processes), circuitry design (e.g., CAD design hardware and software), and device technology.

Assembly and Test: The so-called "back-end" of the microelectronic production process that encapsulates the semiconductor die (or "chips") into a ceramic or plastic package (housing). This category includes the associated bonding equipment (wire bonders and die bonders) and the test machinery used for die-on-wafer testing as well as final packaged circuit testing.

Radiation Hardening: Hardening microelectronics against damage caused by high energy electrons, neutrons, protons, heavy particles, x-rays, and gamma radiation is vital to system performance in hostile radiation environments. Techniques used to accomplish that goal include special circuit designs, application of silicon-on-insulator (SOI) and silicon-on-sapphire (SOS) technology, and processing techniques to reduce radiation sensitivity of the silicon/silicon dioxide interface.

This fabrication technology has widespread use in both military and commercial applications, including computing, communications, and digital electronics. Many special manufacturing problems remain from a military point of view, however. The most important of them involves microcircuit reliability in hostile (i.e., combat) environments. Reliability problems caused by hostile environments often demand specialized manufacturing solutions that may not be available from US industry. Solving these problems remains a critical aspect of DoD fabrication efforts.

B. IMPACT ON US WEAPONS SYSTEMS

Microelectronics technology has pervasive impact for virtually every US weapons system, either current or future. For example, increasing miniaturization techniques allow major modifications of current weapons platforms (such as the creation of aerodynamically unstable aircraft controlled by onboard microprocessors, as for example, on the F-16) to the development of radically new weapons concepts (e.g., "brilliant" weapons). The ability to build in self-test circuitry will greatly reduce maintenance problems. And microelectronics technology also may critically affect operations scenarios and deployment tactics by providing ever increasing decision aids and communications capabilities between tactical/theater commanders and their assets.

Important as microelectronics circuits are today, future weapons systems will rely even more so upon advances in their fabrication techniques. In addition, the ability to design and integrate new microelectronic components into weapons systems is an essential corollary to the device fabrication technology. The success of our future defense posture relies in part on our ability to rapidly exploit advances in microfabrication technology at the systems level.

C. PLANNED R&D

Electron device R&D addresses DoD performance requirements that are often quite generic, and DoD programs are influenced strongly by the materials structures that are realizable as well as by available device processing technology. By the year 2000, the following technologies and capabilities should be ready for incorporation into production development programs:

- Gigahertz-speed signal processing microelectronics components
- Giga-sample analog to digital converter technology
- Submicrometer feature sizes
- Wafer-scale integration of logic and memory devices
- Multilevel (3-D) integrated circuits
- Gigahertz-speed gallium arsenide integrated circuits.

To achieve these results, DoD has extensive microfabrication technology development efforts underway. Perhaps best known is the DoD Very High Speed Integrated Circuits (VHSIC) program. Now in its final phase, the VHSIC program currently is focused upon refining the technologies required to achieve integrated results with submicron (0.5 micron) feature sizes. This will allow fabrication of extremely dense and high-speed integrated circuits. In addition to the VHSIC program, DoD is also engaged in other silicon-based microfabrication technology R&D. In 1989, DoD launched SEMATECH, a DoD/Industry consortium formed in response to Defense Science Board recommendations concerning the domestic semiconductor industry. SEMATECH focuses on advanced commercial technology development. Its specific program is still undergoing evolution. DoD is also pursuing advanced lithography technology (ultra-violet, x-ray, and electron beam), and is developing radiation-hardened semiconductor devices (for both MOS and bipolar device types).

DoD is also developing microelectronics circuits on gallium arsenide (GaAs) substrates as well as on other compound semiconductors. DoD's Microwave and Millimeter-Wave Monolithic Integrated Circuit program (MIMIC) is focused upon the development and production of affordable, reliable analog circuits for use as sensors and signal processors in the front-ends of electronic warfare, radar, smart munitions, and communication systems. These circuits, fabricated primarily from gallium arsenide, operate at frequencies from 1 to 100 GHz. Devices being used include GaAs MESFETs, High Electron Mobility Transistors (HEMTs), and Heterojunction Bipolar Transistors (HBTs). Other programs develop millimeter wave power devices, wafer-scale technology, molecular beam epitaxy and superlattice technology.

DoD is planning a number of technology demonstrations during the 1990-1995 time frame to demonstrate the use of advanced microfabrication technology in the next generation of electronic countermeasure (ECM) systems. The ECM demonstrations will demonstrate microwave jamming (to demonstrate sufficient power levels to counter current/future microwave band radar-directed weapons systems); a counter to emerging millimeter wave radar threats; advanced modulation techniques for jammer power management (to counter the emerging complex modulations and multithreat environment); size/weight/power reduction (to achieve required systems performance under platform payload limitations); and new waveforms to jam low-probability-intercept (LPI) signals.

Total S&T funding for this critical technology* in FY 1990 is on the order of $200 million, and includes:

Microelectronic devices	$ 30 million
SEMATECH	$100 million
MIMIC (excluding GaAs material work)	$ 70 million

D. RELATED R&D IN THE UNITED STATES

The US merchant semiconductor industry spends large sums on R&D (estimated as 15 percent of sales.) Research work involves all major facets of the technology, with special emphasis on cost-reduction bottlenecks (such as clean-room practices and equipment, high-throughput lithography) and new miniaturization techniques (e.g., 3-D scaling processes).

The bulk of this research is applied to development of commercially used microcircuits. While much commercial R&D has direct military input, and vice versa, only about 7 percent of the semiconductor market in recent years has been related to military sales. Therefore, issues of importance to DoD fabrication technology (such as radiation hardening and reliability) might not be emphasized sufficiently in the commercial technology.

* Funding is derived from programs in the DoD budget. Most programs involve several technologies. It then becomes a matter of judgment how many dollars to count in which technology corner. The funding presented here and throughout this report, for each critical technology, is of the right order of magnitude but is generally not a precise budgetary quantity.

Milestones--Microelectronic Circuits and Their Fabrication

	1990	1995	2000
VHSIC electronic circuits providing Highly Reliable and Radiation Hardened Technology	• 0.5 micron low-volume production available in digital silicon devices		
MIMIC electronic circuits providing reliable, analog capabilities for system front-ends	• Numerous single function (amplifiers, oscillators, mixers, switches) chips available in 1 to 20 GHz range • First system demos (HARM, Ger-X, GPS)	• Integrated multiple function ships available over entire 1 to 100 GHz range • CAD/Production facilities available to meet large range of system requirements • Use routine in systems	• Advanced capability chips in use to provide additional capabilities, particularly for higher power mm-wave applications
Commercial SEMATECH Silicon Circuits	• 0.8 micron production capability	• 0.35 micron production capability	
Design	• Test/reliability/process design on advanced parallel computers • Fast prototyping of circuits	• Testable, complex designs generated by scalable design tools • Rapid prototyping to *second level* packaging	• Fail-safe fault tolerant self-repairing adaptivity inherent in microelectronic subsystems
Manufacturing	• *Generic qualification* procedures for gate array microcircuits	• *National quality* procedures for micro-electronics available	

E. COMPARISON WITH OTHER COUNTRIES

Advances in microelectronics support ever-increasing information loads in a broad spectrum of applications. Progress will depend on achieving:

> Higher speed components, with higher speeds attained from either device geometry, or materials (e.g., higher electron mobility, as discussed in Section 2 on gallium arsenide);
>
> Higher levels of integration/component densities (i.e., reduced feature size, larger substrates);
>
> Higher levels of functional integration (e.g., combination of analog/digital functions on a single chip).

The table on the next page provides a summary comparison of US and other nations for selected key aspects of the technology.

Summary Comparison--Microelectronic Circuits and Their Fabrication

	Warsaw Pact	NATO Allies	Japan	Others
High-speed digital processing, either by use of submicron or unique geometries, or the use of GaAs or other high electron-mobility semiconductor materials				Israel, Switzerland
Larger scale integration, to greater component densities or yield in large substrates				Israel South Korea
Higher levels of functional integration, including MMIC and integration of analog/ digital functions on a single substrate				Israel
OVERALL EVALUATION				Israel South Korea

LEGEND:

Position of Warsaw Pact relative to the United States	Capability of allies to contribute to the technology
significant leads in some niches of technology	significantly ahead in some niches of technology
generally on a par with the United States	capable of making major contributions
generally lagging except in some areas	capable of making some contributions
lagging in all important aspects	unlikely to have any immediate contribution

Japan is believed to be ahead of US efforts in GaAs integrated circuit fabrication techniques.

In terms of VLSI/VHSIC-related fabrication, Japan is considered the leader in memory device manufacture, and in most aspects of microelectronics manufacturing, with the exception of microprocessors and application-specific integrated circuits (ASICs).

Our NATO allies, individually, do not presently rival either the US or Japan. This picture could, however, drastically change in the near term. The European countries have extensive capabilities in a number of important niche technologies. The formation of such joint efforts as ESPRIT and the Joint European Submicron Silicon program (JESSI),

coupled with the economic unification of Europe in 1992, can only be expected to enhance the integration and effectiveness of these existing capabilities.

The ESPRIT program is active in the area of Bi-CMOS, and the UK and FRG have developed some significant capabilities in the area of GaAs. These NATO countries are also actively pursuing other advances in silicon-based technologies. JESSI (present participants include Siemens, Philips, and SGS-Thomson of Italy) hopes to extend the consortium's capability in design systems, materials, and fabrication to the 4 M-bit DRAM level. With regard to certain underlying niche technologies, these activities have considerable potential for cooperation.

Within NATO, a large number of companies have active research programs in GaAs and indium phosphide (InP). The University of Edinburgh is reported to have developed a unique design architecture for GaAs digital filters. France appears to be the front runner in promoting and using GaAs devices; NATO companies reported to have active programs include Thompson CSF, Siemens, Telefunken, the Max Planck Institute, Plessey, Philips, the Royal Signals Research Establishment (RSRE), ICI and TNO Physics and Electronics Laboratory (TNO/FEL).

Canada has an active program in computer-aided design (CAD) and basic material research. Waterloo University is reported to have developed a CAD program that characterizes parasitic effects, which are of particular interest in the development of higher density MMIC devices.

As a result of these advances, it is now possible to identify countries with select capabilities which are only slightly behind, equal, or slightly ahead of the best US capabilities. For example:

> UK--Crystal Growth, E-beam lithography, and E-beam diagnostic equipment. Also of interest is the report that a major US firm (IBM) has entered into a contract with a UK firm to purchase compact synchrotrons for its X-ray lithography.
>
> FRG--Silicon crystal growth technology, metallization equipment, X-ray lithography. The FRG is also reported to be s. pplying GaAs chips for one of the next generation (CRAY) supercomputers.
>
> Netherlands--Chemical-vapor deposition (CVD), E-beam lithography.
>
> Switzerland--Wire and die bonders, mask blanks, and thin-film deposition.
>
> Israel--Computer-aided design.

In addition, South Korea is making significant progress, and is reported to have the capability to produce VLSI devices with 1.25 micron or finer feature size. While they appear, for the present, to be drawing on US and Japanese technology, South Korea has the resources and the potential to pursue innovative efforts in the near future. The same appears to be true, but perhaps to a slightly lesser degree, of Taiwan and Hong Kong.

Today, the US microelectronics industry leads all communist country R&D in virtually every area of significance. The Warsaw Pact nations are severely limited in their ability to close the microelectronic technology gap, primarily by their lack of high resolution lithography and other underlying processing technologies.

2. PREPARATION OF GALLIUM ARSENIDE (GaAs) AND OTHER COMPOUND SEMICONDUCTORS

A. SUMMARY DESCRIPTION

Gallium arsenide and other compound semiconductors (such as indium phosphide, indium antimonide, and mercury-cadmium-telluride) have historically played important roles in microwave and millimeter wave circuit devices as well as roles in other wave bands (e.g., infrared and optical). While these materials have had well known potential for still other applications (such as high speed, radiation resistant, integrated circuits), fabrication difficulties prevented the realization of these potential applications. Since 1980, major technology advances have led to greatly improved GaAs materials. Preparation at the molecular level has recently permitted fabrication of the first truly microelectronic integrated circuits on a non-silicon substrate. GaAs technology is expected to become competitive with silicon-based microelectronics, and promises significant advantages over comparable silicon-based devices, especially for military applications.

GaAs circuits will have significant advantages over their silicon-based counterparts because of two intrinsic advantages GaAs has over silicon, namely, a faster electron drift velocity and inherently better resistance to radiation damage. GaAs has an electronic drift velocity nearly seven times faster than does silicon, a significant advantage which can now be exploited. Thus, a GaAs integrated circuit may be many times faster than a silicon-based counterpart of similar design and complexity. Gallium arsenide materials are also inherently less susceptible to damage caused by ionizing radiation (e.g., that experienced in a nuclear blast environment) than is silicon.

Despite its recent breakthroughs, GaAs fabrication technology remains relatively undeveloped compared to more than two decades of research and development in silicon technology. Development and incorporation of GaAs technology into new or existing microfabrication techniques is critical if DoD is to keep pace with materials preparation advances now occurring worldwide. Such developments would also significantly affect existing applications of GaAs technology, especially in millimeter and microwave systems. Preparation technologies include advanced III-V compound semiconductor epitaxy, II-VI compound semiconductor epitaxy, materials handling techniques, and thin film deposition processes and equipment.

B. IMPACT ON US WEAPONS SYSTEMS

GaAs is the most readily available and commonly used material for microwave and millimeter wave frequency devices and circuits. These circuits are critical building blocks for DoD electronic warfare, radar, smart weapons, and communication systems. Their high performance, potentially low cost, unit-to-unit reproducibility and inherent radiation hardness make them essential for performance of front-end functions in these systems.

GaAs now is used in solid-state active aperture antennas (phased arrays). The same integrated circuit elements will appear more commonly in equipment for communications, electronic warfare, and electronic intelligence, avionics, missile guidance and control, and surveillance from space, in the 1990s.

C. PLANNED R&D

DoD is pursuing development of gallium arsenide (GaAs) technology as well as other compound semiconductors. DoD's Microwave and Millimeter-Wave Monolithic Integrated Circuit (MIMIC) program depends on GaAs technology. It, in turn, is complemented by other related programs drawing on GaAs technology, involving fabrication of MESFETs, High Electron Mobility Transistors (HEMTs), Heterojunction Bipolar Transistor (HBT) devices, millimeter wave power devices, wafer-scale technology, epitaxy and superlattice technology, GaAs materials production, molecular beam epitaxy, and dozens of other supporting disciplines.

Work is in progress to develop a high-pressure liquid encapsulated Czockralski (HPLEC) crystal puller fitted with a variety of sensors to allow the reproducible production of larger diameter (4 inches), larger overall size (20-25 kg) boules, of gallium arsenide substrate material with the electrical properties and uniformity necessary to provide starting materials for microwave and millimeter wave devices.

Work is also in progress to improve the control and uniformity of epitaxial gallium arsenide layers. Techniques being developed include Metal Organic Molecular Beam Epitaxy (MOMBE), Molecular Beam Epitaxy (MBE), and Metal Organic Chemical Vapor Deposition (MOCVD). Strategies for the short term are primarily directed toward improving the quality and reproducibility of wafers grown one at a time. Longer range plans call for development of equipment for simultaneous epitaxial growth on multiple gallium arsenide wafers.

Milestones--Preparation of GaAs and Other Compound Semiconductors

	1990	1995	2000
Fabrication of GaAs, etc.	• Production of 4-inch diameter GaAs substrates • Work in progress on improvment of MOMBE and MOCVD single wafer deposition equipment	• Production of 5-inch diameter GaAs substrates • Equipment available for simultaneous epitaxial growth on multiple wafers of GaAs	• Development of reliable sources of InP wafers • Production of 6-inch diameter GaAs substrates

Total S&T funding for gallium arsenide and other compound semiconductor materials technology in FY 190 is on the order of $100 million, including $60 million from SDIO.

D. RELATED R&D IN THE UNITED STATES

The level of US R&D in GaAs preparation technology is increasing as the technology becomes a stronger competitor to existing silicon-based microelectronics. Currently, GaAs R&D investment is not nearly as extensive as is existing silicon-based R&D, but most major US semiconductor firms have efforts underway.

E. COMPARISON WITH OTHER COUNTRIES

Availability of quality material remains a limiting factor in attaining higher levels of integration in GaAs and other compound semiconductors. Once considered almost exclusively of interest for military and space applications because of its inherent environmental and radiation resistant characteristics, GaAs and other compound semiconductors are now being considered for a wide range of applications. These are, primarily, applications requiring a tightly coupled interface between high-speed analog phenomena and digital processing. Thus, compound semiconductors are critical to photonics (Section 7) and to the successful implementation of higher order monolithic microwave integrated circuits.

Key aspects of the technology selected as indicative of significant infrastructure capabilities in GaAs and compound semiconductors are:

- Processing techniques for improving the yield of base materials; and
- Techniques for combining dissimilar semiconductor materials.

The table on the next page provides a summary comparison of US and other nations for selected key aspects of the technology. Principal cooperative opportunities will exist with NATO countries and Japan.

Japan's capabilities in GaAs materials and circuit fabrication could clearly make significant contributions to US capabilities and the needs of the Western alliance.

Japan is the leader in GaAs materials technology, making many of the major materials advances in the late 1970s and early 1980s. European R&D, while significant and growing, is not believed to be as robust as either Japan's or the United States'.

Within NATO, a large number of companies have active research programs in GaAs and InP. France appears to be the front runner in promoting and using GaAs devices. NATO companies reported to have active programs include Thompson CSF, Siemens, Telefunken, the Max Planck Institute, Plessey, Philips, RSRE, ICI and TNO Physics and Electronics Laboratory.

Of interest is the number of European researchers who believe that GaAs will not prove to be the last word in high-speed semiconductor materials. Specifically, InP is believed to offer higher radiation resistance, with higher purity (99.99999 percent claimed) and better fabrication repeatability. This approach is being actively pursued by France (Thompson CSF) and several German firms (e.g., Wacker Chemitronic, GMBH).

Summary Comparison--Preparation of Gallium Arsenide and Other Compound Semiconductors

	Warsaw Pact	NATO Allies	Japan	Others
Preparation of gallium arsenide and other compound semiconductor materials				
Development and growth of complex structures (e.g., strained superlattices) of compound semiconductor materials				
OVERALL EVALUATION				

LEGEND:

Position of Warsaw Pact relative to the United States	Capability of allies to contribute to the technology
significant leads in some niches of technology	significantly ahead in some niches of technology
generally on a par with the United States	capable of making major contributions
generally lagging except in some areas	capable of making some contributions
lagging in all important aspects	unlikely to have any immediate contribution

Also indicative of significant capability in this technology is the Thompson CSF efforts in complex GaAs/GaAlAs and InGaAs/P structures for integrated optics described also in section 7 of this report.

Soviet work in GaAs microelectronics has been a long-standing adjunct to their microwave device R&D, but is believed to lag behind similar advances in the US by at least eight years. Soviet bootstrapping to parity is possible through the theft of technology from Japan and the United States.

3. SOFTWARE PRODUCIBILITY

A. SUMMARY DESCRIPTION

Software has become the focus of functionality and flexibility in most large scale military and commercial systems. The major areas of technical challenge include (1) new capabilities in software systems including high reliability, high assurance, security in all environments, capability to adapt or modify rapidly, and means to guarantee time-constrained response; (2) support for capital-based risk-reduced acquisition approaches, including technology for prototyping in support of requirements engineering and design, and technology for the development and application of reusable software assets; (3) enhancement of software productivity through the integration of advanced software development support tools, reusable software component repositories, and management support tools including cost estimation support; (4) development of operating systems and object management technology to support large scale reliable heterogeneous distributed computing; and (5) development of algorithms, language, and tools to exploit the scaling and performance potential available in advanced computer architectures.

B. IMPACT ON US WEAPON SYSTEMS

Software is a key element of virtually all major weapon systems. Software development and maintenance costs in DoD far exceed computer hardware costs, and are estimated at 6 to 7 percent of the entire DoD budget. Even with costs this high, deficiencies in software affect overall weapons system performance out of proportion to the cost associated with the software. Shifting functionality from hardware to software offers the important advantages of reducing unit replication cost, high flexibility and malleability, and enhanced durability. Rework, maintenance, and evolution account for nearly 85 percent of software costs. Advances in software technology will yield important capability improvements such as (1) very high reliability for secure and life-critical systems, (2) rapid adaptability for systems that must operate in changing environments, (3) reliable and secure large-scale distributed computation for C^3 applications, and (4) access to the performance potential available in low-cost scalable highly parallel hardware.

C. PLANNED R&D

DoD sponsors a broad base of research and development programs in the technologies to support software development, evolution, and maintenance. Major efforts include the Consolidated DoD Software Initiative, which consists of: (1) the Ada program, established to provide life cycle support for the Ada programming language throughout the DoD by providing resources to meet those language support requirements that are common to the DoD Services and agencies; (2) the Software Technology for Adaptable, Reliable Systems (STARS) program, established to develop and demonstrate a software engineering

technology and acquisition practice to economically produce quality military software for weapon systems applications; and (3) the Software Engineering Institute, established to accelerate transition of evolving software technology into the Services and industry for use in development of weapon systems.

In addition, the DoD technology base program sponsors research in (1) distributed and parallel systems, including parallel operating systems and heterogeneous distributed computing; (2) data bases, with an emphasis on distributed object management; (3) algorithms, with an emphasis on exploitation of parallelism; and (4) software design and tools. The latter activity has several focal points, including (1) prototyping language and environment to support requirements engineering and systems design, (2) persistent storage mechanisms for software objects including access control and usage metering, (3) advanced Ada technology for concurrency analysis, real-time systems, and explicit process models, (4) scalable methods and tools for enhancing the predictability of software, including security, safety, and functionality properties, (5) language, analysis, optimization, and refinement tools to support scientific applications on parallel computers, (6) methods to retain and apply software design information to support rapid adaptability, and design reuse, and (7) the development of a common base of tools for data interoperability, user interaction, and heterogeneous systems development.

Total S&T funding for software producibility in FY 1990 is on the order of $70 million, which includes $47 million for the Consolidated Software Initiative (STARS + Ada + SEI).

Milestones--Software Producibility

1990	1995	2000
• Demonstrate means for 2:1 reduction in residual errors in large scale software systems	• Software support tools and methodologies resulting in 5:1 improvement in productivity	• Transformation and optimization of prototypes into production codes by semi-automated techniques
• Develop prototype tools for validation and verification of reusable trusted software code	• Demonstrate 5:1 improvement in reuse of existing trusted software code	• Automated identification and utilization of reusable trusted software code in development of major systems

D. RELATED R&D IN THE UNITED STATES

NSF sponsors basic research in software technology, with an emphasis on theory. Although moderate scale prototype engineering activity is occasionally undertaken, most NSF support is provided to individual researchers working on theoretical problems. DoE supports some work in parallel computing and applications at the DoE laboratories, principally Argonne and Sandia. NASA is sponsoring a major software development environment comparable in focus to the STARS program. Research into computer security, in particular, tends to lag DoD requirements because non-DoD users rarely are faced with the security risks and threats encountered by DoD systems, and because security is frequently outweighed economically in the commercial marketplace by other requirements. Several industrial consortia have been formed in order to address, among

other things, aspects of this technology; the Microelectronics and Computer Technology Corporation (MCC) and the Software Productivity Consortium (SPC) are examples.

E. COMPARISON WITH OTHER COUNTRIES

Key aspects of the technology selected as indicative of significant infrastructure capabilities in software producibility are:

> Software development environments, especially object-oriented automation of requirements and cost analysis, rapid prototyping, and associated library and management support capabilities;
>
> Operating systems and applications to support real-time information management in large, distributed computer operations;
>
> Algorithms, languages, and software engineering tools to take full advantage of the performance potential offered by advanced computer architectures. (See Section 4 on parallel computing architectures.)

The table on the following page provides a summary comparison of US and other nations for selected key aspects of the technology.

Opportunities for cooperation within NATO and Japan will be limited mainly to niche areas associated primarily with supercomputing, specialized methods for exploiting massively parallel architectures, and formal methods for highly reliable and portable software.

A perceived Japanese lead in supercomputing is somewhat offset by a US lead in serial production and applications of lower-cost machines with parallel processing architectures. As of 1987 more than 20 US manufacturers of parallel processors could be identified.

The NATO countries have strong capabilities in selected areas of computer technologies. No single country has competence across as many technologies as does the US. Software development has been an area of emphasis, however, wherein multinational ventures in Europe has the potential for achieving comparability with the US by combining individual strengths. Large-scale European projects are sponsored by ESPRIT and EUREKA using joint industrial/government funding. Total budget for the second phase of ESPRIT is 3.2 billion ECU over five years commencing in 1988. Planning documents indicate that approximately 20 percent of the budget is allocated to software, not including office systems and AI. The EUREKA program, with a total cost of about 4 billion ECU, promotes collaboration through coordination, with funding being provided by the industrial participants. Explicit emphasis is given in ESPRIT to the development of common software interfaces and portable tools. Additional emphasis on the use of formal methods to develop highly reliable software has led to a European lead in many aspects of this area.

In addition to ESPRIT and EUREKA, individual European countries have their own programs, such as the Alvey program in the UK, which has produced effective ongoing industry/university collaborations. Among the NATO nations, the UK evidences perhaps the greatest interest and capability in developing software engineering tools and languages for massively parallel architectures. Netherlands and FRG also have extensive

Summary Comparison--Software Producibility

	Warsaw Pact	NATO Allies	Japan	Others
Enhanced software development environments	■	▨▨	▨▨	
Operating systems and applications software to support real-time information management in large, distributed systems	■	▨▨	▨▨	
Algorithms, languages, and tools for advanced parallel architectures	■	▨▨	▨▨	▨▨ Note 1
OVERALL EVALUATION	■	▨▨	▨▨	▨▨

Note 1. Many countries have ongoing theoretical work in algorithms. Individual breakthroughs are possible from any of these efforts, but cannot be predicted or planned.

LEGEND:

Position of Warsaw Pact relative to the United States		Capability of allies to contribute to the technology	
■■■■	significant leads in some niches of technology	▨▨▨▨	significantly ahead in some niches of technology
■■■	generally on a par with the United States	▨▨▨	capable of making major contributions
■■	generally lagging except in some areas	▨▨	capable of making some contributions
■	lagging in all important aspects	▨	unlikely to have any immediate contribution

efforts addressing a wide range of software engineering topics, including algorithms and software for parallel architectures. French contributions to Ada, and experience in a wide range of specific applications are also evidence of a strong basic infrastructure.

Outside of NATO and Japan, virtually all industrialized nations have some ongoing effort relating to the development of specific algorithms, including research into optimizing the performance of such algorithms on parallel machines. The nature of this research lends itself to individual breakthroughs in specific algorithms. These may contribute to significant advances beyond existing US capabilities, but cannot be predicted or planned for in advance.

The USSR has demonstrated some good theoretical capabilities in computer science. Software continues to be an area of serious deficiency, much of it stemming from

a shortage of computers (especially microcomputers and supercomputers) and from reliability problems (especially with peripherals), and so programmers lack adequate hands-on computer experience. Computer-to-computer networking is rare except in high priority applications. The situation is exacerbated by poor quality public telecommunications (e.g., phone lines) and poor technical communications among S&T professionals.

4. PARALLEL COMPUTER ARCHITECTURES

A. SUMMARY DESCRIPTION

Rapid increases in the performance of computer hardware has been the central driving force of the relentless spread of computing into all areas of military and civilian life. Advanced computer architectures will play a key role in maintaining the existing momentum; in particular, parallel processing offers great promise. Average speed increases of 50 percent per year, sustained for over 30 years, have produced computers capable of executing 10 billion operations per second. Costs falling with equal rapidity have made large-scale parallel systems feasible, opening a path to systems of even higher performance, expected to rise to and above 1 trillion operations per second over the next few years. Major areas of challenge include: (1) integration of heterogeneous processor elements required for digital, symbolic, and signal processing parallel architectures; (2) optimizing the performance of scalable parallel computing systems by developing optimal architectures and internal communication structures; (3) integrating special purpose ultra-performance (>10x generic system performance) into general purpose systems; (4) developing algorithmic approaches which utilize parallel computation effectively; (5) developing effective compiling, operating, and debugging approaches for parallel architectures.

B. IMPACT ON US WEAPON SYSTEMS

Computer systems technology is expected to continue to provide a critical edge arising from superior performance of all classes of weapons and command/control systems which serve as an effective force multiplier. Weapon systems accuracy and corresponding lethality, plus improved performance in naval, ground, and air vehicles, will be impacted. High-performance, dense, embedded systems are crucial for automatic target recognition (ATR) capability by smart weapons. One-thousand-fold performance increases over present systems would find immediate application in large-array anti-submarine warfare (ASW) systems. When combined with communications to provide secure/survivable command and control networks for all components and echelons, a factor-of-three advantage in personnel ratio compared to potential adversaries is expected. Further, technical sophistication of command and control and weapon systems design, production, operation, and maintenance must be comparable to that of the computing technology employed in order to realize its potential.

C. PLANNED R&D

Computing systems are being developed which achieve 1,000-fold performance increases with greater reliability and density, lower cost (factors of 10-20) and higher density through parallelism, i.e., use of many subsystems solving various parts of the information-processing problem at the same time, combined with advanced modular

packaging approaches. Several different models of parallelism are being exploited, with prototypes now in place which compute at rates of billions of operations per second (gigaops), roughly 1,000 times the rate of computing systems now used in defense systems. By the early 1990s, such systems will be packaged in volumes as compact as 10 cubic inches and available for integration in weapons systems. By the mid-1990s, systems capable of trillions of operations per second (teraops) will be available. This is expected to result by the year 2000 in qualitatively new capabilities such as autonomous vehicles, automated image analysis for intelligence, and reduction of planning cycles from days to minutes.

Total S&T funding in this critical technology for FY 1990 is on the order of $80 million, of which $40 million is from DARPA.

Milestones--Parallel Computer Architectures

1990	1995	2000
• 10 Gigaops systems • 1 Gigaop embedded • Optical coupling • Prototype parallel operating system • ASIC modules	• Teraops systems • 100 Gigaop embedded • 3-D memory • Wafer-scale package • Optical routing • Real-time parallel operating system	• 100 Teraops systems • Teraop embedded • Trusted real-time, parallel operating system • Rapid manufacturing for special purpose

D. RELATED R&D IN THE UNITED STATES

Defense investment in high-performance, parallel computing has spawned a number of industrial product lines, mostly oriented toward commercial applications. This in turn has broadened the national technology base and is contributing to the success of the next generation of parallel computing. However, exploitation of massive parallelism into the teraops range generally is seen by industry and other government agencies as too high-risk for development. US industry has instead pursued incremental improvements in older approaches to computing. Federal funding for new machine development comes principally from DARPA, with NSF, DoE, and NASA activities contributing.

E. COMPARISON WITH OTHER COUNTRIES

Parallel computing encompasses a wide variety of different architectures and designs. Key aspects of the technology selected as indicative of significant infrastructure capabilities in parallel computer architectures are:

Underlying component development and fabrication capabilities;

Computer architectural design;

Hardware design and packaging, including techniques for thermal management and power distribution, and high-speed interconnection;

Specialized software engineering, including algorithms, languages, and programming support environments optimized for massively parallel configurations.

The table on the following page provides a summary comparison of US and other nations for selected key aspects of the technology. The US has a significant worldwide lead in serial production and practical application of parallel processing hardware. This lead developed from and continues to be supported by US leads in microprocessors and a broad experience base in advanced computing hardware design and packaging. Principal cooperative opportunities will exist with NATO countries, especially with the UK and the Netherlands in both hardware and software, and with the FRG and France.

Japanese integrated circuit and computing technology could clearly make significant contributions to future hardware developments.

Japan, the UK, Netherlands, and FRG all have credible efforts in advanced computing. The Japanese are the most advanced and, in fact, currently hold the lead in performance of production models of previous generations of computer systems (with limited or no parallel computing). The Japanese are a few years behind the US in highly parallel systems, particularly in the area of system software, but can be expected to close the gap rapidly as significant commercial advantage develops in this area, because they are not as risk-averse as US industry.

The UK has a significant parallel processing software research effort and infrastructure in its universities, industry, and government establishments. Notable among these is the Alvey Program for Advanced Information Technology. The European Strategic Program for Research in Information Technology (ESPRIT) is also pursuing software engineering initiatives. As in the case of the US these efforts may be limited by a lack of computer hardware.

The UK was a primary contributor to the development of the OCCAM programming language--the first general computer language written specifically for parallel computers. INMOS, Limited (Bristol, England) developed, and is currently producing a line of VLSI chips specifically designed to implement the OCCAM language. These chips, called "transputers," are the building blocks of a research program being pursued by the Royal Signals and Radar Establishment (RSRE) with support from Thorn EMI, Ltd., INMOS, and Southampton University to develop a real-time reconfigurable supercomputer.

Recently the Netherlands has become much more active in the field, especially in the area of algorithms and in the area of applying parallel architectures to artificial intelligence.

Japanese R&D in parallel computing is beginning to show results. The Industrial Technology Agency's Electrotechnology Lab has recently announced the development of a 128-processor configuration data flow system, the Sigma-1. The stated maximum processing speed is 640 MFLOPS, placing the system in the supercomputer category.

Summary Comparison--Parallel Computer Architectures

	Warsaw Pact	NATO Allies	Japan	Others
Component development and production				
Computer architectural designs				
Hardware design and packaging, thermal management, power distribution, interconnection				
Specialized software engineering skills, especially those for supercomputing or advanced parallel architectures				
OVERALL EVALUATION				

LEGEND:

Position of Warsaw Pact relative to the United States	Capability of allies to contribute to the technology
significant leads in some niches of technology	significantly ahead in some niches of technology
generally on a par with the United States	capable of making major contributions
generally lagging except in some areas	capable of making some contributions
lagging in all important aspects	unlikely to have any immediate contribution

There is no evidence that the Eastern Bloc has achieved any success in high-performance computing. They have historically followed the US with a 10 or more year lag in computer systems, and there is no evidence this will change unless we give up our advantage by slowing the pace of R&D.

The Soviets are, and will continue to be, severely hampered by lack of capability for quantity production of high-speed digital components and assemblies (see Section 1, Microcircuits). Thus, their capabilities are likely to remain largely in theory, research, and small lot prototyping. While the Soviets have a significant effort in parallel processing in these areas, they are many years from being able to provide their scientists and engineers with the levels of technology presently available to their Western counterparts.

5. MACHINE INTELLIGENCE/ROBOTICS

A. SUMMARY DESCRIPTION

As control of high-performance weapons systems becomes more complex, many become best viewed as tightly coupled man-machine systems, carefully designed to make effective use of the unique capabilities of both man and machine. In some cases, robotics and machine intelligence, when coupled with advances in compact computers, may obviate all human presence in dangerous environments. In other cases, enhancing the man-machine link may prove the difference between victory and defeat in combat.

Machine intelligence and robotics will augment or mimic human intelligence and actions by endowing machines with the capabilities of perception, learning, deduction, induction, and discovery (not usually all together). Components of machine intelligence (e.g., expert systems) and robotics have already proved their commercial worth in moderately complex applications. Military applications range from smart mines, which incorporate both mobility and target sensing/discrimination systems, to unmanned aerial vehicles bearing reconnaissance/ sensing packages, and weapons guidance systems.

When combined with other critical technologies (such as microelectronics fabrication technology and parallel computing technology), machine intelligence will improve automatic target recognition capabilities, allow truly effective diagnostic and prognostic systems, create tactical decision aids, and produce advanced robotic systems. The integration of these technologies will have a significant affect in improving the selectivity and use of sensory inputs. Such improvements will facilitate image understanding and contribute to the new area of speech recognition.

In military systems of the future, machine intelligence and robotics technologies will be comprised of highly integrated subsystems which can sense the outside world from several different perspectives (sensor fusion), and then respond through processing of behavioral knowledge and control actuators to perform specific purposes. These intelligent machines of the future will provide an efficient means to supplement, augment, and support man's capabilities when jeopardized by hazardous conditions.

There are many industrial applications as well, from the handling of hazardous materials to automation in manufacturing. The basic technologies (sensors and processing, control, interfacing, etc.) are the same, only their integration and function are different.

A key requirement for truly autonomous systems lies in the development of sensor subsystems capable of providing robots with high-level information of the environment around them, and on the development of knowledge-based intelligent machines that can process the information to provide the decision-making and control functions in a timely and reactive manner.

B. IMPACT ON US WEAPON SYSTEMS

The battlefield of the future will be fast paced. Sensors and weapons will identify targets virtually on a real-time basis. Intelligent machines will fuse, process, and analyze data and present usable results almost instantaneously. Development of algorithms and associated software to make such systems possible is a major challenge.

In addition to these systems are efforts to develop complex decision-making aids--a Battlefield Management System (BMS). By processing huge amounts of information, machine intelligence can provide much more efficient tools for effective military intelligence, data analysis, battle management assessment, timely decision making, rapid replanning, and survivability through distribution of tasking, machines, and data repositories. Thus, machine intelligence/ robotics applications will reduce the need for manpower while improving human response times. Additional advantages will result from the use of autonomous robotic vehicles and unmanned aerial vehicles. Removing crews from hazardous environments and exposed platforms will improve survivability.

Application of robotics and intelligent machines in manufacturing environments will result in flexible manufacturing capabilities with shortened set-up and production lead times, greater industrial base surge capabilities/capacity, enhanced quality, and reduced acquisition costs. Intelligent self-diagnostic on-line and off-line systems will improve readiness and reduce maintenance and logistics costs.

C. PLANNED R&D

The man-machine interface has become of vital concern in the age of advanced technology weapons and robotics. Man-machine interactions are important not only to specific combatants (e.g., pilots, tank commanders), but also for system logistics, diagnosis and maintenance, battle management assets, and hazardous material handling. Current DoD efforts include addressing on-board diagnostic systems for the M-1 tank, AH-64 and UH-60 helicopters, and for a variety of missile systems. The advantages in terms of battlefield readiness are significant, but even more important is the potential dollars and manpower savings in operation and support costs.

Recent work has shown that such man-machine interface capabilities driven by expert system diagnostics can reduce maintenance manhours by up to 30 percent, component false removals by 50 percent, and maintenance test flight requirements by 50 percent.

The DoD is currently investing in the development of robotic material handling systems for logistic applications, since some of its most critical problems exist in logistics. The success achieved to date in the use of fiber-optic-guided missiles (FOG-M) offers encouragement regarding the potential for tele-operated systems. One particularly interesting example is the use of tele-operated systems as a force multiplier in which one manned vehicle could control a fleet of tele-operated companion vehicles. Today, DoD is succeeding in its efforts to develop a tele-operated mobile platform (TMP) that can serve as an unmanned reconnaissance platform. The DoD has efforts underway to control multiple platforms via a single mobile Robotics Command Center (RCC).

Knowledge representation efforts pervade the applications of machine intelligence. Current efforts are aimed at the following, to mention only a few: (1) developing methods for efficiently encoding and using the difficult-to-structure repertoire of knowledge sometimes called "common sense;" (2) using analogy and past experiences to develop more robust knowledge- and model-based systems that can reason and explain solutions; (3) efficiently representing arbitrary and interrelated spatial regions and intervals of time so that systems behavior can be described; (4) developing methods for the reuse, extension, and integration of knowledge bases without repeating the original investment in knowledge engineering; (5) structuring knowledge so that it can, where applicable, be used in more than one problem domain simultaneously; (6) representing knowledge for problem solving techniques so that it can be applied to classes of problems instead of one problem at a time; and (7) efficiently and automatically passing knowledge and information in a network of distributed problem solvers. These efforts are being carried out in test beds that include development of "smart" unmanned aerial vehicles (UAVs), as well as unmanned ground vehicles (UGVs) and underwater vehicles, "brilliant" (very smart) munitions, signal processing, target recognition, mission planning, and Pilot Associate programs.

Total S&T funding for this critical technology in FY 1990 is on the order of $70 million.

Milestones--Machine Intelligence/Robotics

	1990	1995	2000
Unmanned Ground Vehicle	• Limited autonomous cross country mobility (low speed)--1988	• One operator controls two remotely con-trolled vehicles (RCVs)	• Robotic combat vehicle (one operator controls five RCVs) • Robot vehicle network-ing and interfacing Family of RCVs
Robotic Manipulator	• Field material handling robot technology, 6,000 to 10,000 lbs payload	• Field demonstration of tank loading	• Light-weight robotic vehicle
Data Rate Reduction	• Robotic obstacle breaching assault tank • Tele-operated multi-purpose platform	• Telerobotic vehicle	• Robotic security patrol with remote display and control

D. RELATED R&D IN THE UNITED STATES

Machine intelligence and robotics work in the US is robust, with new enterprises coming to market constantly. Research activity in neural networks has increased particularly in the last three years, with most efforts still at universities but with work increasingly moving toward industrial research laboratories and application groups. About 15 to 20 start-up companies have been formed to exploit the technology in the last two years, with a market of approximately $20 million, primarily for supplying R&D efforts and focusing mainly on computer hardware and software tools for research and prototype

development. A few commercial applications have been developed, including a decision aid for processing mortgage loan applications, a device for reading handprinted amounts on checks, and an assembly line parts inspection application.

E. COMPARISON WITH OTHER COUNTRIES

Machine intelligence and robotics encompass a wide range of diverse technologies and applications. Key aspects of the technology selected as indicative of significant infrastructure capabilities in machine intelligence/robotics are:

- Development and effective integration of smart sensors, i.e., sensors having high resolution and internal processing;
- Development and efficient use of specialized computing architectures including, as a special subset, neural networks;
- Development of specialized software skills for artificial intelligence, knowledge acquisition and engineering, and signal and image processing.

The table on the following page provides a summary comparison of US and other nations for selected key aspects of the technology. Principal cooperative opportunities will exist with NATO countries, especially in the area of software algorithms and image/signal processing applications.

Japan's experience in industrial robots, and its underlying technology base in associated computer science and technology, could make significant contributions to the allies' capabilities if both sides agree to cooperate in robotics technology.

Secondary opportunities for cooperation in niche technologies may be realized in specific niches. Other countries identified as having significant programs include Finland and Sweden, which have evidenced interest in applying neural nets to speech processing and image processing, although these are not considered leading candidates to contribute to significant advances beyond existing US capabilities.

The US has had a commanding lead in computational capabilities, but the lead is being diminished. Japan and, to a lesser extent, some of our European allies have made significant advances in the industrial application of such technology. Much of this R&D is transferable from civil to military applications.

The Japanese Institute of Industrial Technology and Hamamatsu Photonics have jointly developed a rudimentary optical neural computer to explore imaging processing tasks. The goal of the project is to develop "intelligent sensors."

There is limited interest in neural nets within NATO countries, primarily associated with specific applications. The Netherlands and Germany have expressed an interest, primarily in association with their work in 2-D/3-D imaging, which is, in some areas, advancing more rapidly than that of the US and Japan. Within the UK the RSRE has expressed an interest in the area for radar processing applications. The Alvey program has a major effort in adaptive user interfaces that may provide benefit to future neural net applications.

Summary Comparison--Machine Intelligence/Robotics

	Warsaw Pact	NATO Allies	Japan	Others
Development and use of smart sensors				
Specialized computing architectures, including neural networks				
Specialized software engineering skills, especially those for advanced parallel architectures				
OVERALL EVALUATION				Finland Sweden (Note 1)
	Note 1. While not dominant in any key aspect of this technology, Finland and Sweden have reported research in speech and image processing algorithms that may be applicable to neural networks.			

LEGEND:

Position of Warsaw Pact relative to the United States	Capability of allies to contribute to the technology
significant leads in some niches of technology	significantly ahead in some niches of technology
generally on a par with the United States	capable of making major contributions
generally lagging except in some areas	capable of making some contributions
lagging in all important aspects	unlikely to have any immediate contribution

Outside of NATO and Japan, interest and capabilities in neural nets appears limited to specific applications such as speech and image processing. Finland (Helsinki University of Technology) and Sweden (Royal Institute of Technology, Stockholm) have research efforts in the use of neurocomputing to pattern recognition.

The Soviet Bloc significantly lags the US in machine intelligence/robotics. They do have a good theoretical understanding of the area and can show creativeness in applying the technology to selected space and military applications. Its value to battlefield operations as well as to the domestic economy has been recognized and has received political support. Western technology, however, remains critical to Soviet Bloc progress.

There is significant lag in this area by the Soviet Bloc nations, although they have a good theoretical understanding and show creativeness in applying the technology to military purposes. Its criticality in terms of future battlefield operations as well as benefits

to the domestic economy (specifically the accomplishment of basic goals of the national program called Perestroika) has gained Soviet recognition of this technology and ensured incentives to accelerate its development. The availability of Western and Japanese technology, including arrays of technical know-how and manufacturing capability, is critical to the Soviet Bloc and forecasts of their progress.

6. SIMULATION AND MODELING

A. SUMMARY DESCRIPTION

Simulation and modeling technology involves the use of computers to reproduce and evaluate real world situations without involving costly testing or system prototyping. Interactive and non-interactive computer-based simulation and modeling, and its associated analytic simulation techniques, have many applications to design, manufacturing, diagnostics, training, wargaming, battle management, and other important uses.

Physical simulation involves the development of a hardware configuration which can replicate a variety of conditions for both man and machine, such as permitting computer-controlled simulations of both man and hardware in the loop, without having to resort to costly prototypes.

Analytic simulation involves the development of computer models to evaluate procedures and processes in advance of laboratory research efforts or hardware expenditure. Examples include computer algorithms that evaluate new chemical compounds and computers programmed to dynamically demonstrate the influence of vehicle and projectile configuration on air flow patterns. One sophisticated example involves the application of test data to an examination of long gun tube flexing during firing; this data will be invaluable in assessing the impact of new lightweight materials in various armor applications.

Simulation and modeling technology is also enhanced by new developments in computer languages and concepts. For example, Artificial Intelligence (AI) and object-oriented programming paradigms now enable simulations based on computer "objects" that mimic the behavior of real objects. These techniques make complex simulations easier and more affordable.

The application of advanced simulation to very large distributed battlefield simulations will play critical roles in increasing force effectiveness and readiness, and can also focus military system design and procurement by allowing systems to be "prototyped" (in simulation) and used in very large scale simulated battlefield exercises as a way of preparing for actual engagements.

B. IMPACT ON US WEAPON SYSTEMS

Simulation and Modeling technology can be applied to every major DoD weapons development program to reduce design and production cost, improve performance, improve diagnostics and maintenance, assist in better and faster training of personnel, and improve command and control on the battlefield.

Training costs and material wear associated with training can be reduced to the extent that simulators provide the operators (e.g., a tank crew) with a sufficiently realistic interactive simulation of combined arms operations of tanks, armored personnel carriers (APCs), infantry antitank weapons, antitank helicopters, mines, etc. New proposed systems such as vision devices, antitank weapons, and antihelicopter weapons can be simulated digitally so that the utility of given technical parameter requirements can be assessed before hardware is built.

C. PLANNED R&D

Training is an important aspect of Simulation and Modeling technology. DoD currently is using Simulation and Modeling technology to develop a number of important training tools, including advanced wargaming (and troop training) through the SIMNET program, links between the EUCOM Warrior Preparation Center with individual Corps headquarters, F-16 Air Combat Training, tactical combat training, and a host of other specific training programs.

Battle Management technology is also being pursued by DoD. Efforts include development of Environmental and Terrain Space Technology (including Artificial Intelligence links to environmental information), environmental data characterization development, and target recognition based upon the environment. This technology will help reduce the amount of equipment and non-combatants in the battlefield, more effectively use resources, and enhance survivability.

Military Simulation technology constitutes a major portion of DoD's efforts in Modeling and Simulation technology. Current efforts include development and application of missile seeker/smart weapons simulations (used to test especially sensitive systems that would be compromised in open air tests), a full scale LHX cockpit simulation (for pilot reaction to control types and different information displays), Tank Ride and Motion simulation, and "future" systems wargaming exercises.

The SDIO is building a National Test Bed Simulation facility at Falcon AFB, CO. This National Test Bed will be able to simulate a wide variety of SDI-related battle management scenarios and will permit the checkout of newly developed computer modules. There will also be limited opportunities to exercise and evaluate target acquisition, and pointing and tracking hardware systems.

Industrial Simulation can help design and produce military systems of significantly greater functionality. Current DoD efforts in this area include developing engineering trade-off decision simulations, the Transient Radiation Effects on Electronics (TREE) program (designed to simulate the "hardening" processes needed by microcircuits in a nuclear radiation environment), diagnostics of complex systems by modeling a series of "what if" situations until they match the observed failure modes, and so on.

Total S&T funding in this technology is on the order of $115 million, of which $75 million is from SDIO.

Milestones--Simulation and Modeling

	1990	1995	2000
Military Simulation and Modeling	• Object-oriented battlefield simulation environment will allow the fast generation of modern day battlefield scenarios involving thousands of autonomous entities, thereby fostering realism	• Integration of battlefield simulation into a Battle Management testbed to have a test and evaluation approach for new planning and decision aids, pinpointing deficiencies in existing aids as the threat changes, and evaluating the impact of changes in our own doctrine, tactics, weapons, etc.	• Application of knowledge-based techniques for design of complex systems including large software systems and battle management simulations • Demonstration of C3I workstation
Industrial Simulation and Modeling	• Modeling weapon systems performance based on existing hardware to predict system reliability	• Modeling performance of hypothetical designs to help make trade-off decisions for optimum design	• Diagnostics and prognostics by modeling "what if" situations

D. RELATED R&D IN THE UNITED STATES

DoD is building two facilities for the F-14B, each with five internetted trainers. All major airframe manufacturers have networked engineering simulators.

E. COMPARISON WITH OTHER COUNTRIES

Modeling and simulation are applied to a wide range of diverse applications. As the complexity and costs of hardware development increase, designers in all fields will begin to depend more heavily on modeling and simulation. Key aspects of the technology selected as indicative of significant infrastructure capabilities in simulation and modeling are:

Use of advanced computers to attain real-time or faster-than-real-time performance;

Development of effective man-machine interfaces for both design and dynamic training environments;

Specialized software for implementing large knowledge-based systems, including as a special subset those needed to manage large empirically-derived engineering design databases; and

The underlying empirically validated databases required to model processes and effects accurately and realistically.

The table below provides a summary comparison of the US and other nations for selected key aspects of the technology. Principal cooperative opportunities will exist with NATO countries, especially with the UK, FRG, and Canada all of whom have substantial efforts.

Summary Comparison--Simulation and Modeling

	Warsaw Pact	NATO Allies	Japan	Others
Advanced computing for real-time or faster performance				
Effective man/machine interface for design/ training				
Specialized software engineering skills, especially those for large database management				
Empirically validated information bases in substantive areas of interest	(Note 1)			
OVERALL EVALUATION				

Note 1. Soviet knowledge of wargaming and experimental strengths (e.g., in aircraft gas turbines and hypervelocity wind tunnels) will not contribute significantly in this area until computational deficiencies are corrected.

LEGEND:

Position of Warsaw Pact relative to the United States	Capability of allies to contribute to the technology
significant leads in some niches of technology	significantly ahead in some niches of technology
generally on a par with the United States	capable of making major contributions
generally lagging except in some areas	capable of making some contributions
lagging in all important aspects	unlikely to have any immediate contribution

Japan's capabilities in computing and industrial process control also offer promising opportunities in those areas. In general, however, Japan lags the US in its development of empirically validated engineering databases specific to military systems that are required to do effective modeling.

Secondary opportunities for cooperation exist in niche technologies related to modeling of nuclear and solar power (Italy) and modeling of particle accelerators. In addition, the widespread effort in algorithms for parallel processing, such as that ongoing in the Netherlands (described in Section 4, Parallel Computer Architectures) may contribute to advances in numerical methods CFD and hydrodynamic modeling.

Many other countries are active in modeling power and transportation systems. These programs are not, however, considered leading candidates to contribute to significant advances beyond existing US capabilities.

Simulation and modeling as a generic field is established worldwide in civilian applications. Primary applications are found in modeling large complex systems, most notably power (including as an important subset nuclear power), transportation, and telecommunications. These are of only peripheral interest at present: however, these areas could produce advances in software techniques for massively parallel machines that could be transferred to other problems.

Driven by the same economic considerations as the US, our NATO allies are advancing computer modeling and simulation technology. With the exception of Japan, most nations lag in their capability to manufacture high-speed scientific computers. However, there is no restriction to their purchasing these machines. Various national and multinational R&D ventures by our allies may focus on targets of opportunity that would also enhance their overall capability.

Within NATO, the UK is active in a number of areas of interest. These include CFD and modeling of complex communications networks. A number of the NATO countries have ongoing efforts relating to various aspects of modeling spacecraft control and thermal management.

CAE (Canada) is a leader in dynamic training simulation and is contributing presently to the LHX combat mission simulator. Thompson CSF has produced six-degree-of-freedom simulations of the PUMA SA 330 helicopter and the WS 13 LYNX. Specific efforts of interest include improvements in computer generated imagery. These are stated to be adequate to simulate real-time flight dynamics with realistically-textured objects in simulated day, night, and dusk conditions. The ability to do real-time dynamic imagery with detailed texture adds significantly to the training capabilities. This capability is characteristic of the very latest state-of-the-art in US combat mission simulation (as in the AH-64 Weapons System Simulator).

The USSR uses simulation and modeling extensively for conducting war-gaming exercises and weapons development. Although they lag the US in computational capabilities, specifically in large-scale computers and graphics workstations, they nonetheless have good understanding of the subject matter. In some applications, such as war-gaming, their knowledge base of the subject matter may equal or lead that of the US.

7. INTEGRATED OPTICS

A. SUMMARY DESCRIPTION

Integrated optics photonics) encompasses the technology for devices that use light (photons) and electronics (electrons) to perform functions that are now typically performed by electronic devices. The next 20 years will see the emergence of photonic devices in sensor, communication, and information processing systems. Photonics developments can provide major improvements in tactical and strategic C^3I systems. DoD advanced technology developments in photonics include optical memories, optical signal processing, optical computing networks, optical control of phased arrays, integrated opto-electronic networks, and nonlinear optical processing.

B. IMPACT ON US WEAPON SYSTEMS

Integrated optical computing offers order-of-magnitude improvements in processing speed resulting from the natural parallel architecture and high switching speeds of optical devices. In addition, integrated optical circuits eliminate many potentially troublesome connectors and increase reliability. New distributed processing architectures will exploit the absence of metallic wires and concomitant electromagnetic interference problems.

The processing rates for emerging electro-optical and IR sensors, electronic warfare and undersea surveillance are surpassing the capabilities of electronic processing (1-10 Gbit/sec). Dedicated integrated optical processors will soon be needed which act as sensor front ends to preprocess the data and reduce the data rates to those compatible with current and projected electronic processors. Dedicated special purpose integrated optical processors are now in use within DoD in such front end applications.

The table below outlines the goals and payoffs associated with the DoD program in integrated optics:

Goals and Payoffs--Integrated Optics

Application	Goal	Payoff
Integrated Optical Computing	• 100X increase in processing rate • 10X fewer physical hook-ups • Distributed architecture • Reduced EMI susceptibility	• Greatly improved ECCM capability for all types of sensors (IR, radar, EW, acoustic, etc.) • Enable processing of data from high density (>10^6 element) focal plane arrays and very large phased arrays

C. PLANNED R&D

DoD has a broad-based R&D program in integrated optical signal processing, microwave/millimeter wave photonic processing, optical networks, and photonics materials. The DoD program includes developments of semiconductor lasers, optical modulators and switches as well as integrated optical designs incorporating such devices. This program includes developments oriented toward specific applications, including a promising program in integrated optical processing for spread-spectrum signals.

Total S&T funding for this critical technology in FY 1990 is on the order of $25 million.

Milestones--Integrated Optics

	1990	1995	2000
Cryptography	• Cryptos required for security communications. Processing speed less than 50 MOPS	• Limited intrusion detection secure communications without crypto	• Secure optical communications without crypto
Integrated Optical Devices	• 5.25-inch tactical optical disk with 300 megabyte data capability	• 10X improvement in spatial light modulators and dynamic range • 10X increase in networking capability/ speed • 10X decrease in input/ output bottlenecks • 14-inch tactical optical disk with 6-gigabyte data capability	• 14-inch jukebox tactical optical disk with 120-gigabyte data capability
Sensor Applications	--	--	• 1 GOPS signal processing • High capacity (10^{12} BPS) local area networks • High accuracy/high density light-weight phased array antennas • Improve ELINT option processor by several orders of magnitude • All optical surveillance and communications systems performing simultaneous operations with no individual function performance penalty

D. RELATED R&D IN THE UNITED STATES

A number of other government agencies support R&D in integrated optics. There is also a large industrial R&D effort in the technology, particularly in the telecommunications industry.

Several universities have established consortia with industry and/or government partners to pursue work in optical computing. These include: the Optical Circuitry Cooperative at the University of Arizona's Optical Sciences Center, the University of Southern California's Center for Photonic Technology, the University of Alabama at Huntsville's Center for Applied Optics, and the Center for Optoelectronic Computing Systems at the University of Colorado.

E. COMPARISON WITH OTHER COUNTRIES

Integrated optics (photonics) depends on both light (photons) and electronics (electrons) to improve devices usually operating only electronically. The next 20 years will see the emergence of photonic systems composed of sensors, interconnections, communications, and optical information processing that operate principally in the domain of photons (light signals). Photonics developments aim to provide major improvements in tactical and strategic C^3I systems with faster, smaller, and more survivable systems. Advanced technology developments in photonics include optical memories, signal and adaptive processing, computing networks, optical control of phased arrays, integrated optoelectronic networks, optical transmission, and non-linear optical processing.

Key aspects of the technology selected as indicative of significant infrastructure capabilities in integrated optics are:

- Materials and manufacturing techniques for integrated electronic and photonic/optical devices on a single chip or substrate;
- Materials and manufacturing techniques for optical switching devices;
- Optical interconnections (i.e., guided or unguided, focused or unfocused photonic paths instead of wires);
- Optical beam steering devices (i.e., diffraction by holographic elements or cross-bar switching devices);
- Two-dimensional spatial light modulators; and
- Computer-generated holographs.

The table on the following page provides a summary comparison of US and other nations for selected key aspects of the technology. The United States and Japan share a worldwide lead in this technology. Our NATO allies have significant efforts that, in aggregate, have the potential to rival either the US or Japan. The commercial and military potential of these integrated optics are such that most of the industrialized countries of the world are making a significant national commitment. 'forts and capabilities vary from one country to another depending upon the particular fo.in of government and economy. In some cases there is a very strong governmental involvement (e.g., the Soviet and Japanese efforts), in others there is a much stronger university thrust (e.g., Europe). The result of this diverse effort, however, is a widespread multidisciplined international effort. The US

Summary Comparison--Integrated Optics

	Warsaw Pact	NATO Allies	Japan	Others
Materials and manufacturing techniques for integrated optics				China
Materials/manufacturing techniques for optical switching				
Optical interconnection techniques				Israel
Optical beam steering devices				
Two-dimensional spatial light modulators				
Computer-generated holographics				China
OVERALL EVALUATION				China, Israel

LEGEND:

Position of Warsaw Pact relative to the United States	Capability of allies to contribute to the technology
significant leads in some niches of technology	significantly ahead in some niches of technology
generally on a par with the United States	capable of making major contributions
generally lagging except in some areas	capable of making some contributions
lagging in all important aspects	unlikely to have any immediate contribution

and the Allied countries vary in leading and lagging each other in the development and production of state-of-the-art photonic devices and applications. In specific areas, countries other than the United States are the recognized (or suspected) leaders. Overall, Japan appears to lead in long-range product planning, product innovation, and market share, although some leads are by a slim margin. Principal cooperative opportunities will exist with NATO and Japan, especially in applications of compound semiconductor superlattices and organic non-linear optical materials.

Japanese technology in integrated optics and in its effective application to optical communications (see Section 8, fiber optics) could also offer significant contributions.

There are emerging opportunities for cooperation in niche technologies involving fabrication of bistable devices. These devices are essential to realizing a digital optical computer and are the object of intensive research worldwide.

Other countries identified as having significant programs include Israel, S. Korea, and China. These programs are not considered leading candidates to contribute to significant advances beyond existing US capabilities, but there exists the possibility for worthwhile innovations.

NATO activity involves government, industry, and universities. The largest government/industrial participants include:

Plessey Research Ltd. (UK)

Philips Laboratories (UK, W. Germany, Netherlands)

Thomson Laboratories (France)

Siemens (FRG).

European effort in electro-optics is likely to benefit from the initiation of a new, all-European professional society, Europtica. This is expected to have an integrating effect on work now underway in:

Advanced optoelectronic technology

Quantum wells and superlattices

Materials

Focal plane arrays

Optical interconnections

as well as to the application of these technologies to remote sensing, imaging, and industrial processes.

France appears dominant in the area of integrated optics per se with active research in optically bi-stable and high-speed optical switching. Other basic research is being carried out with complex GaAs/GaAlAs and InGaAs/P structures. The UK, FRG, and France are also active in the field of quantum wells and superlattices for optical and integrated optical devices.

Both France and the UK have ongoing basic research in organic non-linear optical materials. While additional research into techniques for practical fabrication is needed, claims are that the materials offer efficiencies two orders of magnitude higher than the commonly used Lithium Niobate, LiNbO3, with sub-picosecond response times.

One of the largest optical computing programs in Europe has been the European Joint Optical Bistability Project. This involves eight universities and institutes in the United Kingdom, Belgium, West Germany, Italy, and France. In France research is being conducted on liquid-crystal light components at the University of Paris (Orsay). Thompson-CSF also is pursuing a major effort on optical processing. In West Germany, Erlangen University is investigating parallel logic, optical cross-bar switches, spatial filtering, and logical operations using polarized light. The University of Duisburg has built

a very fast electro-optic multiplier and broadcast bus. This will support communications between modules in a computer. The Fraunhofer Institute has developed an optical local area network.

Japan is pursuing research and development in all areas of optical processing. Government, industry, and universities are all heavily involved. The key government participant is the Ministry of International Trade and Industry (MITI). Most of the large electronics companies in Japan have made a commitment to this effort. The Optoelectronic Industry and Technology Development Association (OITDA) is a special trade organization founded in 1980 to coordinate industrial activity, foster cooperation, and encourage standardization. Universities in Japan are also playing a key role. They perform much of the basic materials research on which the technology development is so dependent. In 1984 the Japan Society of Applied Physics established a research body called the Optical Computer Group. This illustrates how seriously Japan is taking the field of optical computing. The group has members from universities, government laboratories, and private companies. As of August 1986, it had sponsored 15 meetings and published 13 issues of its journal called OPCOM NEWS. In summary, Japan has a large, well coordinated program addressing all aspects of optics.

Japanese commitment to integrated optics is a natural consequence of their dominance in the field of fiber optics (see also Section 8, Fiber Optics). For example, NEC has recently reported an experimental optoelectronic receiver, using high-mismatch epitaxy of GaAs and InP, capable of handling 2 Gb/second modulation rates. They also are the free-world leaders in optical communications within computers.

A number of companies in Israel are involved in the optical area. Most of this effort involves electro-optics, lasers, and fiber optics. Optical sensors, guidance, and imaging devices of high quality are commercially available. Medical imaging systems, robotic vision, optical inspection systems, and night vision devices are all in advanced development or commercial stages.

The Chinese are also very active in this area and have sent many students to US universities to study photonics. As a result, China has demonstrated a growing capability in the optical area. This effort includes fiber optics, optical sensors, communications, optical signal processing, and holography. In addition, China has recently emerged as the primary source of certain single crystals for use in nonlinear optics.

8. FIBER OPTICS

A. SUMMARY DESCRIPTION

During the past decade, fiber optics has greatly increased in importance not only in DoD but also in the commercial sector. The next decade will see a proliferation of DoD systems which rely on fiber optics to perform their functions. Today's fiber optics will provide ships, aircraft, and undersea communications with higher bandwidth capabilities at lower cost than cable approaches. Ultra low-loss fluoride fibers with their theoretical loss of 10^{-3} dB/km will permit transoceanic repeaterless links which could revolutionize undersea surveillance, long distance communications, and tethered vehicles such as fiber guided missiles. Fiber optical sensors will provide a new class of gyros as well as acoustic, magnetic sensors for inertial navigation, antisubmarine warfare, and commercial applications. DoD's research and development efforts in fiber optics support all of these applications as well as optical components, fiber optic cabling, and fiber coatings.

Ultra low loss fiber optics technology is an area of great importance to DoD. This technology consists of optical fibers fabricated with zirconium fluoride (ZrF) glasses. These glasses are the lowest scatter material ever produced and represent a major advance in glass chemistry. This technology is critical to feasibility of such systems as large aperture, high-gain, acoustic arrays (thousands of acoustic sensors interconnected over tens of kilometers), and long-range command guided anti-ship missiles. Continued integration of electronic processors and controllers with fiber optical devices, improved interconnects, switches and multiplexers, and higher power, frequency tunable optical sources are important elements of this technology.

B. IMPACT ON US WEAPON SYSTEMS

The superiority of fiber optic communication over copper-based systems can be measured by information-carrying capacity (four orders of magnitude greater for optical systems), energy loss in signal transmission (two orders of magnitude lower), error rate (one order of magnitude lower), and the resistance to electromagnetic interference (EMI). Future developments in semiconductor lasers promise still greater improvements in data rate capacity and link margin.

Ultra low-loss fiber optics will support a number of critical military capabilities:

- Wide area surveillance
- Undersea and tactical missile guidance (low-cost, target and aimpoint selection)
- Remote surveillance and tele-operated weapons platforms (removing requirement for personnel to enter high-threat areas).

Fiber optic communication links will add a whole new range of capabilities for weapon guidance, since they provide for wideband, non-line-of-sight, two-way communication. The Fiber-Optic-Guided Missile (FOG-M) is a prototype which illustrates some of these capabilities. As a tank or helicopter killer, FOG-M can fly over the horizon and provide a television or infrared image to the gunner, who guides it to the target while he stays in a safe location. Advances made in fiber optics technology will provide future local area voice and data communications networks with more reliability and survivability. The tactical fiber optic local area networks can satisfy the need to distribute command posts by providing high capacity interconnection.

Fiber optical sensors support major improvements in ASW surveillance as well as providing the basis for autonomous underwater vehicle guidance. Future acoustic towed arrays from surface ships and submarines require at least 10 times the number of acoustic channels in either multi-line or extra long arrays. Fiber acoustic sensor arrays appear to offer the best approach for this application. High-performance, high-gain planar fiber acoustic arrays offer significantly increased capabilities. Bottom-mounted acoustic fiber sensor arrays connected by fiber optic telemetry cables will play a key role in enhancing the Navy's capability to counter the quieted Soviet submarine threat.

Finally, fiber optical gyros offer order-of-magnitude lower cost for weapon and autonomous vehicle guidance. Fiber gyros are small, all solid state with no moving parts, rugged and reliable. Additionally, order-of-magnitude improvement in accuracy over state-of-the-art gyros is possible with fiber gyros which incorporate ultra low loss fibers.

C. PLANNED R&D

There are a number of DoD programs in fiber optics, fiber optic sensors, and semiconductor lasers of various types. Applications likely to be ready for full scale engineering by the year 2000 include fiber guided missiles, fiber optic local area networks operating at data rates up to 5 to 10 Gbit/sec, fiber optic communication systems for land and sea with bandwidths in excess of 20 GHz, high speed computer interconnects using fiber optics, phased array control by an optically-fed harness to the transmit/receive elements, and intrusion detection systems made with optical fibers.

Ultra low-loss fiber optic technology is being pursued by DoD in its technology base and advanced technology demonstration programs, and can be expected to be available for incorporation in engineering developments by the mid- to late-1990s. The Army is also developing a rugged, non-kinking fiber optic cable for the FOG-M.

Total S&T funding for this critical technology in FY 1990 is on the order of $20 million.

Milestones--Fiber Optics

	1990	1995	2000
Undersea Surveillance		• Demonstrate distributed fiber optic sensor (10X the number of acoustic channels)	• Distributed fiber optic sensor in FSD
Local Area Networks (LAN)	• 1 Gbit/sec LAN	• 5 Gbit/sec LAN	• 10 Gbit/sec LAN
Undersea Cabling		• Demonstration of 20 GHz bandwidth	
Fiber Optic Gyro	• Demonstration of fiber optic gyro (FOG)	• Demonstration of FOG incorporating ultra low-loss fibers (10X increase in accuracy over ESG)	• Demonstration of FOG with 100X increase in accuracy over ESG

D. RELATED R&D IN THE UNITED STATES

Almost every government agency is involved in some aspect of fiber optics. There is also a very large industrial involvement in the technology and numerous commercial applications. Fiber optics has become the mainstay for the telecommunication industry. Fiber sensors are being employed in medical, process control, and safety monitoring applications, to name a few.

US research in single mode fiber optic systems is driven by increased demand for bandwidth. Looking to high definition television, even with data compression requirements for data transfer rates of 135 Mb/sec may be needed. There are presently a number of experimental projects to introduce fiber optics to provide commercial combined information and television service to homes. One of these will provide the initial test of microwave frequency (2 Gb/s) subcarrier multiplexing.

American National Standards Institute and international acceptance of standardized formats and interfaces will further speed introduction and development of optical fibers in the US commercial market. The higher data rates required are pushing designers to the use of single mode fibers. There have been several successful demonstrations of the use of fiber optics for multi-channel (up to 60 in one case) television transmission.

E. COMPARISON WITH OTHER COUNTRIES

Fiber optics technology is key to development of very high (gigabit or greater) data links, especially in military applications requiring electromagnetic hardening. The requirement for higher data rates is forcing the art to smaller diameter, single-mode fibers. A special application of optical fibers is in sensors, including undersea fiber-optic sensor systems and inertial rate sensors for guidance and control.

Key aspects of the technology selected as indicative of significant infrastructure capabilities in fiber optics are:

> Development of improved production methods for long ultra-low loss fibers;
>
> Development of improved techniques and components for interconnections, including integrated transmitters and detectors; and
>
> Improved characterization of non-linear properties of single mode fibers, and development of special fibers for use in fiber optic sensing elements.

The table on the following page provides a summary comparison of US and other nations for selected key aspects of the technology. The US and Japan share a worldwide lead in this technology. Japanese technology could clearly make significant contributions. Cooperative opportunities will also exist with NATO countries, especially in niche technologies relating to associated components required to fully exploit low-loss fiber capabilities.

Secondary opportunities for cooperation in niche technologies may ultimately be realized with Israel, South Korea, and Sweden. These countries have significant programs in areas of interest. They are not, however, considered leading candidates to contribute to significant advances beyond existing capabilities found in the US, NATO, and Japan.

Japan clearly leads the world in converting R&D in fiber optic technologies to various commercial applications and has manufactured considerable amounts of low-loss optical fiber (e.g., less than 0.1 db/km). The Japanese have a major investment in both fiber optics and the ancillary photonic devices needed to use them effectively. To a lesser extent, the UK, France, and the Federal Republic of Germany and/or other Third World countries can also produce low-loss optical fibers but may have difficulty in producing such fibers in large quantities.

A number of countries are actively pursuing related topics. In 1988 the Japanese (Fujitsu) demonstrated the first broadband optical ISDN. NEC has demonstrated an experimental optoelectronic receiver, using reported development of high-mismatch epitaxy of GaAs and InP, capable of 2 Gb/second modulation rates. A number of Japanese firms and British Telecom in the UK are pursuing coherent communication techniques that are advertised as having near-term potential to extend transmission capabilities to 4Gb/sec. If realized, these would be significant advances. The UK is also doing research into special fibers (high-birefringence, polarization-preserving) for sensor applications.

Outside of NATO there is also evidence of a significant body of military research in two areas of interest. Both Sweden and Switzerland are reporting research in a range of topics of military interest, including radiation effects, short pulse response, and sensors. Australian development of large optical slip rings may also be of interest for practical integration of fiber optics into military systems (e.g., mechanically rotating armored vehicle turrets).

In key component areas both Sweden (Ericsson) and Japan (NEC) have reported development of integrated all-optical switches for use with single-mode fibers. France (Corning) has reported development of an innovative use of integrated optics fabrication techniques to produce single-mode couplers, dividers, and multiplexers.

Summary Comparison--Fiber Optics

	Warsaw Pact	NATO Allies	Japan	Others
Development of improved production methods for long ultra-low loss fibers				Various Sources
Components and interconnections				
Characterization of non-linear properties of single mode fibers for sensors				
OVERALL EVALUATION				Various Sources

LEGEND:

Position of Warsaw Pact relative to the United States	Capability of allies to contribute to the technology
significant leads in some niches of technology	*significantly ahead in some niches of* technology
generally on a par with the United States	capable of making major contributions
generally lagging except in some areas	capable of making some contributions
lagging in all important aspects	unlikely to have any immediate contribution

Korea is conducting research and development in some areas of optics. Most of their effort involves the more mature optical technologies, lasers and fiber optics. They are not at the forefront of research in any area of optics. This may change, however, since they are forming joint ventures with US and Japanese firms. The largest Korean electronics firms (Gold Star, Samsung, Daewoo, Hyundai) are active in a number of technological areas. These include microcomputers, VCRs, CD players, laser printers, fiber optic Local Area Networks, hybrid ICs, and VLSI level semiconductor chips. These capabilities will serve them well when they become more diversified in the optical processing arena.

9. SENSITIVE RADARS

A. SUMMARY DESCRIPTION

Continued reduction in target observables will significantly reduce the range of existing US surveillance and sensing capabilities. Multispectral surveillance (wideband radar, bistatic radar, laser radar) will be required to handle the advanced low observable threats and counter stealth technology. Multispectral surveillance forces the enemy to reduce observables across many frequency bands, and increases robustness and sensitivity of radars.

Non-cooperative targets challenge radar technology not only in low observability. Detection of a non-cooperative or non-communicative (possibly neutral) target is not sufficient basis for action. The target needs to be classified (is it aircraft or missile, tanker or destroyer?), recognized (is it friend or foe, armed or unarmed?), and identified (is it the same target seen in another place or at another time?). The microwave, millimeter wave, or laser radar must possess new sensitivities.

This requires a number of high-resolution radar technologies, including inverse synthetic aperture radar (ISAR), millimeter-wave (MMW), and high-range-resolution (HRR) radar. The ISAR technique is well suited for naval applications because ships are moving targets which pitch and roll with the sea; ISAR can image aircraft as well. Millimeter-wave technology is a lower-cost, high-resolution option. High-range-resolution radar produces high resolution in range only, but is less costly than ISAR. Bistatic radar which separates the radar transmitter and receiver, possibly by hundreds of miles, and eliminates radar emissions from the receiving platform, making it hard to detect.

Lasers hold great promise for ultra-short wavelength radar transmitters. The decrease in operating wavelength by more than four orders of magnitude would lead to dramatic decreases in antenna sizes and support structures, thus leading to much more compact systems. DoD has a significant effort in laser radar development, particularly for strategic defense applications.

Adaptive techniques applied in space (phased arrays) and time (waveforms) can seek out and focus on targets, reduce sidelobes, increase resolution, and null out interference (e.g., jammers).

B. IMPACT ON US WEAPON SYSTEMS

Radar sensor technology, both at RF and laser frequencies, will remain a major factor in future warfare. It is crucial that techniques be developed to counter threat efforts to reduce their signatures. Further, the dynamics and range of future engagements will force a greater reliance on real-time non-cooperative target recognition (NCTR). The goals and payoffs of thrusts in this technology are outlined below.

Goals and Payoffs--Sensitive Radars

Sensor Type	Goal	Payoff
Radar (monostatic, multistatic) and ESM	• Counter 10^3 reduction in observables • Counter threat reduction of RF emissions	• Counter emerging stealth threat • Improved ECCM capabilities and operation in severe environments (high clutter; operation on board high acceleration missiles)
Concealed Target Detection Sensors (High resolution/ Imaging Radar)	• Enhanced wide area search and detection of targets in clutter • Low frequency SAR with wide angle/polarization diversity	• Long-range detection of mobile military targets under all weather conditions • Reliable detection of concealed/camouflaged military targets
Laser Radar	• Rapid, accurate hand-off to SDI weapon fire control • Effective discrimination of RV threats for non-threat objects • 3-D characterization of concealed tactical targets	• High resolution, large volume surveillance for strategic defense • RV discrimination against full range of penetration aids • 3-D sensor for tactical ATR system
NCTR	• Effective ID of low observables targets in near real time	• Real time non-cooperative ID in complex tactical environments

C. PLANNED R&D

The DoD Low Observable (LO) program is developing and demonstrating multispectral technologies addressing detection, tracking, and non-cooperative classification of advanced airborne threats (primarily stealth cruise missiles) in the future countermeasures environment. The program includes UHF/L-band radar, dual-band radar, and infrared (IR) sensors, airborne bistatic radar, and the associated sensor fusion. The program has completed and assessed several designs for the airborne radar. Multisensor fusion for improved tracking has also been demonstrated. The ongoing program will address (1) multiband radar components; (2) IR sensor concepts and demonstrations; (3) bistatic radar concepts and demonstrations; and (4) associated algorithms and processing schemes.

Modular LPI radars are being developed for UAV or elevated platform payloads and multistatic radars using a dedicated transmitter and a combination of moving and stationary receivers. The transmitter for a multistatic radar can be either expendable or positioned in a sanctuary (possibly on a satellite). The DoD program is addressing countermeasures to anti-radiation missiles (ARM-CM). The results of this work are being used in the development of the multirole, survivable radar (MRSR) for air defense. The Multisensor Target Acquisition System (MTAS) program is an effort to apply synergistic multisensor processing to a millimeter-wave radar and FLIR or other electro-optical sensors to achieve highly reliable, all weather target detection and ATR.

Another DoD R&D program is for a wide area search/cueing sensor to enable reliable detection of targets situated in various kinds of tree cover/foliage or camouflage.

Such a sensor must be capable of operation in all weather and in all seasons. It will require the development of a low frequency synthetic aperture radar employing wide angle and polarization diversity and must provide the capability of high signal-to-noise (detection) with low false alarms.

The SDI laser radar program is developing space-based technologies for fire control, discrimination, and active imaging of strategic threat objects. The technologies being developed include high-power laser transmitters, detectors, beam steering concepts, modulators, amplifiers, signal processing techniques, and related analytic tools for fire control, discrimination, and imaging applications.

Total S&T funding for this critical technology in FY 1990 is on the order of $170 million, including $130 million from SDIO (mostly for laser radars).

Milestones--Sensitive Radars

	1990	1995	2000
Radar (monostatic, multistatic) and ESM	• Determine effectiveness of HRR techniques	• Demonstrate multi-static radar for UAV	• Demonstrate anti-stealth radar concepts
Laser Radar	• Airborne measurements of simulated strategic threats	• General demonstration of capability for strategic defense	
Concealed Target Detection Sensor (high resolution/ imaging radar)	• Determine target/ background clutter phenomenology • Establish sensor design goals	• Design/develop wide area search sensor • Develop automatic detection algorithms • Flight test capability	• Initiate FSED program
NCTR	• Determine effectiveness of HRR radar for NCTR • Evaluate new radar approaches	• Develop data base and algorithms for NCTR radar	• Initiate FSED on NCTR

D. RELATED R&D IN THE UNITED STATES

DoD's laser radar developments are coordinated with NASA and R&D programs at defense contractors. The NASA program is developing coherent laser radars for space-based measurement of windfields and turbulence mapping. Significant industrial R&D has occurred on high efficiency diode laser pumping of solid state lasers.

SAR and multi-spectral sensors are being pursued for commercial use in earth resource mapping.

E. COMPARISON WITH OTHER COUNTRIES

Key aspects of the technology selected as indicative of significant infrastructure capabilities in sensitive radars are:

Development/integration of high-resolution, multi-spectral sensors;

Development of high-frequency/high-resolution radar, including laser radar;

Use of high-throughput computational techniques to discriminate, classify, and identify targets.

Secondary opportunities for cooperation in niche technologies may be realized through cooperation with Sweden under proper security measures.

Summary Comparison--Sensitive Radars

	Warsaw Pact	NATO Allies	Japan	Others
Development and use of high resolution multi-spectral sensors	■	▨	▨	
High frequency/high resolution radar/laser radar	■	▨	▨	▨ Sweden (Note 1)
High throughput computational techniques	■	▨	▨	
OVERALL EVALUATION	■	▨	▨	▨ Sweden (Note 1)

Note 1. While not predominant in any key aspect of this technology, Sweden has reported some interesting research in target characterization with high resolution laser radar.

LEGEND:

Position of Warsaw Pact relative to the United States

- ■ significant leads in some niches of technology
- ■ generally on a par with the United States
- ■ generally lagging except in some areas
- ■ lagging in all important aspect

Capability of allies to contribute to the technology

- ▨ significantly ahead in some niches of technology
- ▨ capable of making major contributions
- ▨ capable of making some contributions
- ▨ unlikely to have any immediate contribution

The UK, France, and the FRG report ongoing efforts in SAR/ISAR technology, as well as basic programs in techniques for distinguishing targets of interest in high clutter

environments. France and Germany are actively pursuing joint investigation of the use of laser radar for helicopter detection and recognition. Both France and Norway are studying the use of imaging techniques against surface targets (ships, armor, etc.).

There is significant R&D in the UK on coherent radar signal processing, and in synthetic aperture radar imaging at the FRG Aerospace Research and Development Center.

There are ongoing cooperative efforts with the UK in the area of rugged military laser (radar) transmitters.

Outside of NATO, Sweden appears to have a significant effort covering a wide range of topics relating directly to NCTR. Of particular note is a program involving the characterization of aircraft target features with a CO_2 laser radar.

10. PASSIVE SENSORS

A. SUMMARY DESCRIPTION

Passive sensors detect electromagnetic energy and include IR, visible, UV, and x-ray sensors, superconducting electromagnetic sensors, and ESM, radar and electronic warfare sensors.

IR, visible, UV, and x-ray sensors include a range of novel focal plane array approaches. Mercury-cadmium-telluride, HgCdTe (HCT), operating at higher temperatures but at shorter wavelengths (short wave and medium wave IR) than silicon, is being developed to detect long wave IR (LWIR), yet barriers remain in the manufacturing of large focal plane arrays. Doped silicon that operates at temperatures less than 20 kelvin and is sensitive in the medium and long wave IR bands is being developed for single and dual spectrum imaging systems. Silicon impurity band conduction (IBC) detectors are now emerging as a viable detector. Efforts are underway to improve their sensitivity, nuclear survivability, and ease of production.

Superconducting quantum interference devices (SQUIDs) are being developed for use in superconducting electro-magnetic sensors. Such sensors will make particularly important contributions at very low frequencies (ELF, VLF).

Passive RF sensors are also being developed within DoD's Technology Base program. Microwave radiometry is emerging as an important sensor given its resolution and its range in poor weather (as compared to passive IR systems).

Diagnostic sensors integrated with weapon systems and measuring performance parameters in real time can diagnose incipient problems and predict impending failures, thus greatly improving maintainability and availability.

B. IMPACT ON US WEAPON SYSTEMS

Passive sensor technology is a major factor in providing a technological edge to US forces by enhancing detection, localization, classification, identification, and tracking capabilities, as highlighted below. Passive sensing is a critical adjunct to US stealth efforts. The effective exploitation of passive sensors can enable US system survivability even in high threat environments.

Goals and Payoffs--Passive Sensors

Sensor Type	Goal	Payoff
Multispectral Passive Sensors	• Techniques and data base to exploit signatures across spectrum	• Counter stealth • Exploit full range of target observables
EO/IR Sensors	• 10^3X more detectors per focal plane • Much greater producibility • High resistance diode detector arrays for high sensitivity • Low-noise signal processing chips • Nondestructive in-process testing	• Enable passive sensor operation with very high resolution and good ECCM capabilities (e.g., for use in ship air defense) • Crucial to overall US edge in satellite surveillance (real-time, high-resolution capability)
Microwave Radiometry	• Demonstrate micrad sensor effectiveness in tactical applications	• Enable passive sensor operation at moderate resolutions in poor weather • Exploit an available threat emitter signature
Integrated Diagnostic Sensors	• 10X reduction in maintenance downtime	• Improved weapon system sustainability under wartime conditions

C. PLANNED R&D

DoD has a substantial technology base effort in passive IR, visible, UV, and x-ray sensors to improve battlefield capabilities, improve target acquisition performance, and in particular, improve sensitivity in adverse weather. Emerging LWIR systems feature 64x64, 3-mil pixel displays, with 128x128, 2-mil pixel systems anticipated in the near future. At these resolutions, the systems are approaching the fundamental limits achievable in ferroelectrics, and basic research into both materials and photoelectronic mechanisms will be needed to achicve further resolution. Mid-wave sensors have been produced with 488x640 array sizes using platinum silicide material. IR sensors are being developed for space applications, both for strategic defense and air defense. DoD is also working to improve the sensitivity of visible, UV, and x-ray detectors. DoD is also investing in small, reliable coolers, particularly for space applications.

IRST technology for long-range search, target acquisition, and track is being pursued for fleet air defense, high altitude UAVs, ship self defense, and aircraft target detection. This DoD program also includes an IR background measurements and analysis program. Background discrimination remains a significant problem for such infrared sensors.

DoD has maintained a broadbased program for wide area surveillance of air targets using various space-based IR sensors. The current emphasis is on development of scanning IR sensor techniques and the associated clutter rejection algorithms.

The DoD program in microwave radiometry is at a very early stage of evolution. The focus remains on phenomenology-signature measurements, propagation, and

backgrounds. Sensor concepts are being studied for several applications (e.g., ship classification).

DoD efforts in multispectral sensing are incorporating a number of passive sensor techniques. The DoD Low Observable (LO) program is developing and demonstrating techniques for integration of passive RF and IR sensor inputs. A number of other multisensor efforts are pursuing similar technologies in other applications.

Primary emphasis of R&D in integrated diagnostic sensors is toward technology demonstrations. There are generic demonstrations associated with physical condition monitoring (e.g., measuring and recording stress on electronic devices during operational exercises) as well as weapon specific demonstrations. There are programs developing integrated demonstration of on-board adaptive diagnostic systems. New weapon system development programs include extensive analysis during the demonstration-validation phase of the additional physical condition sensor requirements beyond basic operational performance requirements for each subsystem. These analyses show much payback for a small number of added diagnostic sensors and control, reporting and analysis systems. In the next five years R&D will emphasize smart integrated sensors, extended environmental performance range, and the development of on-board and off-board intelligent analysis and processing support systems.

Total S&T funding for this critical technology in FY 1990 is on the order of $170 million, including $90 million from SDIO.

D. RELATED R&D IN THE UNITED STATES

The DoD efforts in developing passive IR technology are coordinated with both NASA and industry. There are a small number of research efforts at universities and at the national laboratories on superconducting sensors (both RF and IR) and strained superlattice detectors. The total funding of these programs is relatively small compared to the DoD effort (less than $10 million per year). Since there is no commercial market for sensitive passive arrays, industrial funding is minimal, while NASA programs usually build one-of-a-kind arrays. The only area in which current non-DoD funding is significant in supporting related research is in materials development for superconductors. The NASA efforts in cryogenic cooling are similar to those of DoD; however, their FY 1989 funding level is only about $1.4 million. Industrial R&D is significantly less than that.

Research and development in the integration of diagnostic sensor technology is proceeding rapidly in certain US industries--commercial aircraft manufacturers and operators, the power industry, computer, communication, and electronics industry, and the automotive industry. The automotive industry has gone beyond many other industries by developing the customized condition sensors and significant condition analysis systems for on-board and off-board use.

E. COMPARISON WITH OTHER COUNTRIES

Passive sensors encompass a wide range of measures supporting clandestine surveillance and detection of enemy forces. These range from passive optical sensors through low frequency acoustic systems for undersea detection of submarines.

Milestones--Passive Sensors

	1990	1995	2000
Multispectral Passive Sensors	• Fusion at track and post detection level of single frequency band sensors (acoustic through optical) • Wideband (decade level) passive microwave sensors	• Multifrequency band monostatic radar technology available • Pre-detection single frequency band sensor fusion capability	• Wideband monostatic radars available • Multicolor IR sensors displayed • Fusion of multiple wideband sensors
EO/IR Sensors	• MWIR InSb producibility • MWIR platinum silicide producibility	• Demonstrate VLWIR silicon impurity band conduction (IBC) technology • Radiation hardness demonstration • MWIR/LWIR HgCdTe producibility demonstration • Five-year space qualified cooler	• Superconducting LWIR and VLWIR detectors • Strained-larger superlattice IR detectors • GaAs and Germanium multiplexers • Monolithic superconducting LWIR with readout electronics
Microwave Radiometry	• Data base of target and background signatures	• Laboratory demonstration of Micrad sensor	• Anti-ship sensor demonstration Anti-tank sensor demonstration
Integrated Diagnostic Sensors	• Demonstration of partially integrated diagnostic sensors on existing weapon systems	• Demonstration of partially integrated diagnostics sensors on a new weapon system	• No scheduled maintenance for many weapon subsystems • Integrated diagnostic sensor on all new weapon systems

Key aspects of the technology selected as indicative of significant infrastructure capabilities in passive radars are:

Development of large two-dimensional focal plane arrays;

Development of improved techniques for microwave and millimeter-wave radiometry;

Application of superconductive sensors; and

Development of techniques for multi-sensor data fusion

as well as the evolution of technology for more effective application of such sensors in integrated diagnostics.

In general, the US is ahead of our allies in all aspects of passive sensing technology. The table on the following page provides a summary comparison of US and other nations for selected key aspects of the technology. Principal cooperative opportunities will exist with NATO countries, especially with Germany (which is already producing the US modular FLIR detector under US license) and with the UK. In addition, the basic research in compound semiconductor materials and integrated optics may provide opportunities for advancing the state of the art.

Secondary opportunities for cooperation in niche technologies may be realized in Japan, whose solid-state technology could clearly make significant contributions. However, Japan's experience in the long-wave IR regions for military sensors is limited.

Another country identified as having significant programs is Israel. This program is more likely to contribute to novel applications than to advance US technology per se.

Silicon thin film impurity band conduction (IBC) technology was discovered in the US and is export controlled. As a result, silicon research by our allies is primarily on bulk materials. There are reports that German industry is working on silicon IBC devices.

Research and development of mercury-cadmium-telluride (HCT) is conducted by the British, French, and Israelis; and the FRG is presently producing the linear HCT detector array used in the US modular FLIR. Again, the R&D efforts are minimal compared to the US effort due to the difference in need for strategic sensors for national defense. The British are well behind in production and test capability but are very competitive in passivation (encapsulation) techniques and understanding of HCT detectors. There are reports that the French have developed a process to develop HCT detectors that are superior optically to those made in the US. This process has been recently licensed to a US company. The Japanese have reported IR detection using superconducting materials; however, it does not appear to be a concerted effort.

Only the British have a space-qualified cryocooler. This Stirling cooler has been life tested for a five-year equivalent period and is currently being produced. This technology is not yet available to the US. Philips (Netherlands) and the FRG have been identified as sources of closed/split-Stirling cycle coolers for IR detectors. Israel has advertised a cooler similar to that currently used on the TOW night sight, but details of its performance and reliability are not known. The Italians are aggressively working on magnetic refrigerators and have tested a no-moving-parts cooler.

The Japanese are ahead of the US in the area of multi-band-capable components using dissimilar compound semiconductor materials (e.g., GaAs with InP).

Considerable effort has been expended investigating multispectral sensor technology throughout NATO. There is an equivalent FRG SADARM, and there is a multinational Precision Guided Smart Munition Program. The USAF is initiating a cooperative program with Japan to fashion a hybrid seeker system. In general, however, foreign efforts trail the US state of the art.

Summary Comparison--Passive Sensors

	Warsaw Pact	NATO Allies	Japan	Others
Development of large focal plane arrays			Note 1	Israel
Improved techniques for microwave and millimeter wave radiometry				
Application of super-conductive sensors				
Development of techniques for multisensor data fusion				
OVERALL EVALUATION				Israel

Note 1. While not predominant in military IR detectors, Japanese capabilities could provide underlying technologies in compound semiconductors and fabrication of large focal plane arrays.

LEGEND:

Position of Warsaw Pact relative to the United States	Capability of allies to contribute to the technology
significant leads in some niches of technology	significantly ahead in some niches of technology
generally on a par with the United States	capable of making major contributions
generally lagging except in some areas	capable of making some contributions
lagging in all important aspects	unlikely to have any immediate contribution

In the area of fiber optic sensors the Allies are performing research and development on a number of sensors, across the entire electromagnetic spectrum, for many commercial, industrial, and military purposes. Many Allied countries are conducting research concerning different optical fiber coating materials in order to increase fiber optic sensor (FOS) sensitivity for such uses as strain, vibration, and temperature measurements.

The Allies are doing conceptual and proof of feasibility work in the Integrated Diagnostic Sensor Technology area. The open literature shows work in microsensor or integrated sensor technology in the UK, West Germany, the Netherlands, Japan, and Italy. Japan appears to have the largest body of work in the literature after the United States.

Eastern Bloc countries have continued their development of HCT detectors. Literature from Poland indicates continued progress in improved performance. The Soviets are believed to have developed a FLIR using a linear HCT array detector for use on tanks

and possibly helicopters. There is little evidence, however, of mass production and deployment of FLIR systems to date.

The Soviets are pursuing Stirling cycle coolers for space applications; however, they lag domestic development in terms of long lifetime and high reliability. They have published results of innovative concepts utilizing pulse tube refrigerators and appear to be far ahead of the US in this technology.

11. AUTOMATIC TARGET RECOGNITION

A. SUMMARY DESCRIPTION

Dramatic advances in automatic target recognition (ATR) technology have made possible significant advances in conventional weaponry over the past 20 years, both in missiles and on launch platforms. Signal processing technology has advanced to the point where many functions previously performed by military operators can be performed effectively by combinations of sensors and signal processing systems. Automation of operator functions in the highly dynamic and hostile environment to be expected in future warfare will enable stand-off weapon engagement capabilities not otherwise possible.

Although the term ATRs is used for simplicity, one usually distinguishes between classification (is it a destroyer or a freighter?), recognition (is it friendly or hostile?), and identification (what is the aircraft tail number?). ATR may be active (using radar returns) or passive (using a TV image).

ATR technology is the combination of computer architecture, software, and advanced signal processing techniques developed to meet the increasing numbers of threats and the increased number of sensors needed to counter stealth, to automate operations to avoid overloading human operators, and to process more complex signals from advanced sensors. This technology includes those techniques for multi-sensor integration associated with "smart" weapons.

Most conventional ATR systems continue to adhere to a classical paradigm of preprocessing, detection, segmentation, property measurement, and classification. A variety of approaches to the last part of the problem, classification, have been developed. These approaches, in order of historical appearance, are as follows:

- *Correlation of Matched Filter Techniques.* Correlation classification involves taking the cross correlation between representations in 1-, 2-, or 3-dimensional space. The correlations must be taken for all target aspect angles and sizes and for all positions in interest in the surveillance field. The process tends to be computationally very intense and is therefore well suited to multi-dimensional optical correlators. Model-based classification is a recent variant of correlation classification.
- *Model-Based Approaches.* This involves reduction of target images to features in the form of line segment orientations and relative locations. These are then extracted and passed to a knowledge-engineered process of logical operations which identify one of a set of target classes. It is also necessary with this technique to accommodate the wide variations in target aspect angle, although the process can be made invariant to apparent target size.
- *Neural Networks.* The implementation of this approach to recognition differs fundamentally from the previous two in that recognition is carried out in a

distributed multi-layer array of nonlinear elements which are interconnected by adjustable linear networks whose weights can be altered through training on known tar',et images. Neural network processors are fundamentally different from classical Von Neumann digital processors in that they have no central processing memories, or software. Research in this area is still in a very early stage.

B. IMPACT ON US WEAPON SYSTEMS

Application of ATR technology to conventional weapon systems offers significant advantages. Although fully automatic ATR is not expected in the near term, there are immediate opportunities in undersea targeting, small land-attack stand-off weapon guidance, over-the-horizon targeting, airborne multiple-target fire control, ATR for anti-ship and other air-to-surface missiles, automatic target acquisition with airborne synthetic aperture radar, and automatic target cueing (ATC) assistance in finding strategic relocatable targets (SRT), to name but a few.

The table on the next page summarizes the current state-of-the-art in ATR technology as well as the long term potential of ATR technology.

C. PLANNED R&D

The DoD program for development of signal processing technology contains all the fundamental elements that are required for an ATR systems development program, namely: signatures, algorithm development, hardware development, and component and systems testing. The program goals are guided by the intended application (e.g., the Army effort is focused on LHX requirements for target acquisition) but encompass other more generic aspects as well.

A central element of DoD's automatic target recognition (ATR) program is the development of a real time ATR processor, the Multifunction Target Acquisition Processor (MTAP), representing advances in both algorithms and electronics. Algorithms are the foundation of all signal processors and provide the mathematical constructs for detecting and recognizing targets autonomously. Current approaches are analytic, incorporating a priori clutter and target information by means of a model-based approach. The main thrust is based on developing a mathematical model of targets and backgrounds for synthesizing laser radar, millimeter wave radar, FLIR, and ESM images.

Enhanced testing capabilities are being developed with an electronic terrain board used to simulate passive IR signatures of military targets in realistic backgrounds. These synthetic methods are being expanded to include a variety of active and passive sensors (e.g., FLIR, LADAR, and MM Wave), with emphasis on validating their realism. DoD is developing standard, reproducible test and evaluation methods for signal processors, acceptable to industry. The focus is a test facility in which sensors and processors will be tested as integrated systems.

DoD has numerous ATR technology programs aimed at automatic targeting of undersea targets. Current systems are man-intensive and require the integration of data from many sources. Proliferation of threats much increases the volume of data to be

Goals and Payoffs--Automatic Target Recognition

Targets	Current State-of-the-Art	Long-Term Potential
Fixed high value ground targets (e.g., bridges, hangars)	• Ready for advanced engineering development (laser and IR techniques) • Promising techniques within the technology base	• More robust techniques will evolve
Ships at sea or in harbors	• Technology potentially available (SAR/ISAR) for advanced engineering development	• Potential for near automatic recognition capability
Moving targets in moderate/low clutter (e.g., aircraft against clear sky)	• Technology potentially available using non-cooperative target recognition techniques (e.g., conventional or MM-wave radar)	• Move to more automation of recognition function
Unobscured fixed land targets in benign backgrounds (tank in desert)	• Within state-of-the-art for cueing (IR) • Ready for advanced technology demonstration	• Move to more robust cueing and eventually to automatic recognition • Switch to multi-sensor approaches and laser radar
Moving targets in cluttered background	• Still a subject of research or early exploratory development	• Not likely to achieve full automation • Pilot will remain in the loop
Fixed land targets in highly cluttered backgrounds/partially obscured (tank in bushes or trees)	• Still a subject of research or early exploratory development	• Success uncertain • Technology will evolve with this as a future goal
Strategic relocatable targets	• Promising techniques emerging (e.g., SAR/ISAR)	• Limited capability possible in time • Capability against obscured targets and countermeasures much less certain

processed and automation of the target recognition process is needed. ATR technology applicable to over-the-horizon, autonomous anti-ship missiles is being investigated. A program for air targets is being conducted which shares the generic technology portion with anti-surface weapons developments.

The Image Processing Language (Image Algebra) will lay a mathematical foundation for digital image processing operations, standardize algorithm notation, demonstrate algebraic capabilities, and demonstrate algorithm optimization techniques. The Model-Based Imagery Sensor Target Exploitation and Recognition program is developing multi-sensor model-based algorithm design tools.

Computer Vision and Image Understanding is being developed using knowledge-based software. Computer vision will be applied to autonomous smart weapons. A prototype image interpretation system (SCORPIUS) is being developed for demonstration in the exploitation of imagery obtained from reconnaissance systems. Another program

(ADRIES) is developing model-based algorithms for the interpretation of synthetic aperture radar imagery. The algorithms are based on tactics, terrain, doctrine, and other battlefield limitations to deduce the existence of target arrays. In millimeter wave sensor technology, algorithms will be developed using the data collected by a dedicated sensor designed to provide standard sensor data in several modes.

Other programs include automatic radar air-to-ground target acquisition, which will demonstrate a real-time implementation of model-based vision algorithm on a parallel processing computer using images derived from an airborne synthetic aperture radar; an ATR to counter CCD (camouflage, concealment, and deception), which will develop model-based vision algorithms to find camouflaged, concealed tactical targets amongst decoys and other enemy deception techniques using passive infrared and a carbon dioxide (CO_2) laser radar; and a strategic relocatable target (SRT)/automatic target cueing (ATC) capability, which is to demonstrate automatic cueing assistance to offensive weapons system officers looking for Soviet relocatable missiles from a manned airborne synthetic aperture radar, as well as other candidate sensors, and combinations thereof.

Total S&T funding for this critical technology in FY 1990 is on the order of $75 million.

Milestones--Automatic Target Recognition

	1990	1995	2000
Algorithms	• Statistical ATR evaluations • Real-time model-based combined with statistical techniques • Simple sensor fusion concepts • Limited feedback • Limited scene context • Track file, ID, and fire control fusion-real time	• Model-based algorithms, high fidelity target models • Supervised Hardwired neural network algorithms • Multi-level sensor fusion • Increased feedback • Improved scene context	• Advanced perception algorithms • Adaptive nonsupervised neural network. • Multiple feedback between algorithm spaces • Complex scene understanding
Model Development	• Target models for radar, laser radar, electro-optical sensors • Single sensor approaches	• High fidelity target, low fidelity background models for radar, laser radar, electro-optical imaging sensors • Fused prediction models for multi-sensors: UV, IR, laser radar, radar, ESM, RWR	• High fidelity target, CCD background, atmosphere, sensor models for complete system prediction analysis • Addition of high countermeasures environment capability

D. RELATED R&D IN THE UNITED STATES

In signal processing technology DoD and industry objectives often coincide, hence there is strong interaction, especially in the technology base. However, ATR system design, architecture, and algorithms for weapons applications are often unique.

E. COMPARISON WITH OTHER COUNTRIES

Automatic Target Recognition involves specialized sensors, processors and algorithms for real-time acquisition, analysis, discrimination, and recognition of specific targets.

Key aspects of the technology selected as indicative of significant infrastructure capabilities in automatic target recognition are:

- Improved sensors with higher resolution and improved on-board processing;
- High-speed signal and data conversion, involving higher levels of functional integration (See also discussion in Section 1, Microelectronics); and
- Development and refinement of empirically-derived databases and models characterizing targets of interest and clutter and propagation phenomena.

The table on the following page provides a summary comparison of US and other nations for selected key aspects of this technology. The US enjoys a significant lead over other countries in the area of automatic target recognition, and in the development and use of the extensive databases needed to support this effort. Effective application of the technology has the potential to reveal sensitive information regarding US threat intelligence and the inherent weaknesses of US systems.

While classification of sensitive information may preclude extensive cooperation on specific techniques and systems, much of the work ongoing in NATO, Sweden and Israel could contribute to the advancement of smart sensors, and algorithms applicable to ATR. Work in the UK, FRG, and France in advanced detector materials and MMIC technologies are also promising.

Specifically in the area of high speed data conversion (primarily A/D conversion), European efforts are proceeding in BiCMOS (integrated bipolar and CMOS on a single chip) under the ESPRIT program. This is also the subject of independent efforts in the UK and Netherlands.

In the area of processing algorithms and techniques, there is widespread activity. Both the FRG and Netherlands are working on techniques for 3D image processing and filtering for estimation.

Summary Comparison--Automatic Target Recognition

	Warsaw Pact	NATO Allies	Japan	Others
Development of improved smart sensors				
High speed signal and data conversion				
Empirically validated engineering databases on targets and clutter				
OVERALL EVALUATION				Israel Sweden (Note 1)
	Note 1. Sensitive nature of ATR technology may limit cooperative opportunities. However, Japanese technologies described in Sections 1 and 2 could contribute to critical component developments.			

LEGEND.

Position of Warsaw Pact relative to the United States	Capability of allies to contribute to the technology
significant leads in some niches of technology	significantly ahead in some niches of technology
generally on a par with the United States	capable of making major contributions
generally lagging except in some areas	capable of making some contributions
lagging in all important aspects	unlikely to have any immediate contribution

12. PHASED ARRAYS

A. SUMMARY DESCRIPTION

Early radar systems incorporated parabolic or paraboloidal reflectors, which were physically pointed and scanned through the desired azimuth and elevation angles to sweep over the desired volume. An alternate method of scanning developed mainly since the 1960s replaced mechanical scanning with electronic scanning through changing the phase of many small individual radiating elements. By correctly shifting the inputs of the individual radiators, the radar beam can be steered throughout a very large solid angle, without mechanical motion. Phased arrays have found wide application in DoD radars as well as in passive RF sensors.

In acoustic sensors, there has been a similar trend toward the use of phased arrays. Acoustic arrays are now a mainstay of US Navy ASW.

Phased array R&D is essentially a signal processing technology which includes system architecture, processing algorithms, and components (RF and digital). The focus of DoD R&D is on providing the basis for complex computations in near real time for phased array systems. Of particular interest are those cases involving non-Gaussian interference and non-stationary noise. New receiver structures are being developed to handle these cases. Adaptive processors are being investigated to deal with distributed jammers and other distributed interfering sources such as shipping in the case of acoustic systems. Large aperture array systems are being investigated to increase array gain and obtain increased resolution for interference suppression. Conformal arrays are also being pursued which allow for the sensor to be built into the hull or skin of the platform.

B. IMPACT ON US WEAPONS SYSTEMS

Active array antennas utilize solid-state modules (transmit/receive modules) installed behind each radiating element. These modules allow all of the transmit and receive functions to be physically placed on the antenna assembly. By distributing these across the antenna, high power RF tubes and feed circuitry are eliminated. The energy distribution over the larger volume reduces cooling requirements. Improvements in cooling increase reliability and lead to lower cost of ownership. Having all receiver functions at the aperture reduces line losses and contributes to improved performance of the total radar system.

To meet the demands of modern warfare, future airborne phased array antennas, along with dish antennas, must be located within the structural envelope of the aircraft and require radomes to transmit and receive energy. A logical extension of technology would be to develop radomes and antennas as a unit that conform to the skin structure of the aircraft, thus resulting in conformal arrays. By embedding the transmit/receive electronics into the conformal array and adding health sensing, the concept produces a "smart skin."

For example, fiber optics located in the composite material could monitor the structural integrity of the aircraft.

Such conformal arrays provide improvements to aerodynamic configurations by eliminating the need for pods, blisters, or domes. If the entire surface of a large aircraft is used as a sensor, expensive structural modifications to aircraft such as AWACS would be eliminated. Thus, the large radar antenna system currently required by the aircraft could be eliminated and they could no longer be identified from any other aircraft in the fleet by this physical attribute. For high performance aerodynamic aircraft, such as B-1s, phased arrays could be used for communication terminals, eliminating the high-drag blisters that may be required to house the satellite communication antennas.

A major threat to DoD radars is the ability of enemy units to detect their emissions and to target them with antiradiation missiles. In order to counter this threat, DoD is developing low-probability-of-intercept (LPI) phased-array radars ("Quiet Radars") which use one or more of very narrow beams, very low sidelobes, and steerable sidelobe nulls. The latter allows the system to automatically tune out jamming or to deny a signal to a known enemy receiver. Phased array technology makes this possible.

US Navy control of surface and subsurface ocean areas has been put at risk by rapid Soviet progress in submarine quieting and other submarine acoustic technologies. New acoustic array capabilities are being developed for the SSN-21 program as well as other major platforms.

C. PLANNED R&D

DoD has a very aggressive technology base program in phased array technology, particularly for acoustic arrays and conformal RF arrays ("smart skins").

DoD is pursuing active and passive acoustic array technologies. Programs in the acoustic arrays include: high-gain conformal acoustic arrays; broadband arrays; ocean bottom sensors; and torpedo guidance and control.

The Electronic Combat Multifunction Radar (EMR) development is a long term technology effort to develop a robust electronic counter-countermeasure (ECCM) design concept and critical components for a post-1995 generation fire control radar system that is invulnerable to enemy electronic countermeasures (ECM) and that can automatically adapt to mission requirements. The EMR system will also provide supplemental ECM and electronic support measure (ESM) functions.

RF conformal array (smart skin) sensors are also being actively developed for aircraft and will provide multispectral information as well as being designed for multifunctional use (i.e., radar, EW, communication, etc.). Arrays of sensors will be dispersed or distributed over a large portion of the aircraft surface such that very wide field of view sensing can be provided. Smart skins will provide greatly enhanced integration of avionics capabilities in conjunction with a superior ability to totally assess situational awareness.

Total S&T funding for this critical technology in FY 1990 is on the order of $80 million, which is about half acoustic and about half microwave.

Milestones--Phased Arrays

	1990	1995	2000
Conformal RF Phased Arrays	• Airborne, multimode radars	• Airborne, multifunction systems	• "Smart skins" technology aircraft
Acoustic Phased Arrays		• Long range active sonar	• Large aperture, high gain passive acoustic array

D. RELATED R&D IN THE UNITED STATES

ASW sensors share a common technology base and were originally derived from marine seismic streamers. Research ongoing in the area of geophysical processing may prove to be directly applicable to active towed array systems.

To date radar phased array systems have been too expensive for use in air traffic control systems. The availability of lower-cost, solid-state, active array modules, coupled with increasing requirements for higher traffic handling capability can be expected to make phased array technology an area of greater interest for commercial application.

E. COMPARISON WITH OTHER COUNTRIES

As the name implies, phased array technology involves the use of an extended array of sensors whose outputs are processed to improve spatial resolution. The technology also allows the beam to be switched electronically. This permits a single radar to track multiple targets simultaneously, and to adapt the beam shape to minimize or reduce the effects of unintentional interference or electronic countermeasures.

Acoustic array ASW sensors share a common technology base and were originally derived from marine seismic streamers. Research ongoing in the area of geophysical processing may prove to be directly applicable to active towed array systems.

Key aspects of the technology selected as indicative of significant infrastructure capabilities in phased arrays are:

Development of conformal arrays, allowing the use of phased arrays on advanced platforms with minimum degradation of mobility;

Devclopment of active low-frequency sonar to counter Soviet advances in submarine quieting; and

Successful exploitation of new parallel processing capabilities to attain higher processing rates.

The table below provides a summary comparison of US and other nations for selected key aspects of the technology. By virtue of many years of defense research, the US has established a significant lead over other nations, particularly in the development of air- and ship-borne phased-array radar. Opportunities for cooperation in niche technologies

may be realized in specific areas including active arrays and in selected components and applications of parallel computing.

Summary Comparison--Phased Arrays

	Warsaw Pact	NATO Allies	Japan	Others
Development of conformal arrays	■	▨	▨	
Development of low-frequency active sonar	■	▨	▨	
Techniques for exploiting advanced parallel architectures	■	▨	▨	
OVERALL EVALUATION	■	▨ (Note 1)	▨ (Note 2)	▨ Israel

Note 1. While not predominant in any key aspect of this technology, the UK and France have specific capabilities of interest.

Note 2. In comparison to the United States, Japan has limited experience in fielding operational phased array radars. Their experience in gallium arsenide could, however, make a significant contribution to US development of active phased arrays.

LEGEND:

Position of Warsaw Pact relative to the United States		Capability of allies to contribute to the technology	
■	significant leads in some niches of technology	▨	significantly ahead in some niches of technology
■	generally on a par with the United States	▨	capable of making major contributions
■	generally lagging except in some areas	▨	capable of making some contributions
■	lagging in all important aspects	▨	unlikely to have any immediate contribution

The US has had many years of practical experience in radar phased arrays, and has a significant lead over the rest of the world. The allies may still, however, be able to make significant contributions in specific areas of MMIC and in the application of GaAs modules to active arrays.

Related phased array work is being performed by many NATO countries, Japan, and others. In the UK, the Admiralty Research Establishment is pursuing development of an active phased array system based on solid state GaAs modules. Ongoing work at the Royal Signals and Radar Establishment, in conjunction with INMOS Ltd, and Oxford University is of interest for the development of massively parallel signal processors for sonar and radar applications. The FRG has developed a prototype phased array for air

defense applications, and Thompson CSF is reported to have a significant capability in phased array design.

The Japanese have fielded a phased array mortar-locating radar, the J/MPQ-P7. It is believed to be technologically inferior to its US counterpart. The Japanese have a very strong capability in gallium arsenide used to fabricate microwave phased-array components. Specific design and fabrication techniques may lead the US in some respects, and could contribute significantly to the development of materials and components for active-element phased arrays.

Regarding marine acoustic arrays, the UK and French have programs in ASW towed arrays. These are not believed to be comparable to the latest US Technology. There is no evidence of any significant developments focused on large-aperture, high-gain acoustic arrays per se.

13. DATA FUSION

A. SUMMARY DESCRIPTION

The dramatic advances in data processing technology have enabled significant advances in C^3I and battle management over the last 20 years, both on the launch platforms and at fixed or mobile ground stations. Data processing technology has advanced to the point where many functions previously performed by military operators and intelligence analysts can be performed effectively by data processing systems. The increasing complexity and speed of warfare combined with rapid advances in computer and communications technologies is driving the more effective integration of multiple sensors and diverse sources of information. Data fusion technology includes data processing techniques for a wide range of military applications from battle management to cockpit display integration.

B. IMPACT ON US WEAPONS SYSTEMS

Data fusion technology offers significant opportunities for advanced battle management and C^3I systems. Data fusion techniques are essential to counter adversary use of stealth technology (e.g., acoustic quieting, low RCS, low IR signature) and to aid in wide area target surveillance in hostile and cluttered environments. Data fusion is particularly important for global or large-area surveillance and targeting. It will have wide impact assisting theater commanders in wide area surveillance from space as well as underseas, predicting environmental conditions, managing distributed assets such as in electronic warfare; as well as assisting platform commanders such as ATF/ATA pilots in their future "super cockpit," or helicopter pilots with their nap-of-the-earth navigation; and will impact on all command and control functions.

C. PLANNED R&D

The DoD program for the development of data fusion technology includes collection and modeling of target signatures, algorithm development, hardware development and testing systems and integration.

A significant DoD program is the Army's Distributed IEW fusion system which is designed to (1) receive input data from an integrated sensor system (via multilevel security channels, (2) perform adaptive intelligence fusion/analysis of data, and (3) utilize self-learning capability to enhance system performance. This effort, which is intended to assist in planning, directing, and controlling battlefield operations, will be the subject of various subsystem demonstrations during the 1991-96 timeframe.

In multi-sensor fusion for target acquisition and identification (ID), advanced model-based vision techniques are being developed to enhance confidence in target ID. Initial efforts focus on intra-radar signature fusion in which an algorithm suite will exploit ultra-high resolution ranging radar. Expansions will include RWR, IR, laser radar, UV, and ESM sensor inputs under the program called Multi-Attribute ID Analysis. The end result is a comprehensive algorithm suite for fusing multiple sensor inputs for air and ground targets at a feature level.

In undersea surveillance, the Navy has numerous signal processing technology programs aimed at fusion of signals detected by different acoustic arrays. Current systems are man-intensive and require fusion of data from many sources. Proliferation of threats greatly increases the volume of data to be processed and automation of the target recognition process is needed.

In area denial, the Army's wide-area mine (WAM) system has been augmented by acoustic and seismic sensors which can detect vehicles up to 300 meters, can distinguish between tracked and regular vehicles, heavy and light armed vehicles, US versus Soviet vehicles, etc. This is followed up by locating and attacking the target by appropriate means. The WAM is equipped with sufficient CMOS electronics to perform the data fusion without human assistance.

The battlefield of the future will move at a rapid pace. Sensors and weapons will identify targets virtually on a real-time basis. Data processing techniques are needed to fuse, process, and analyze data from many sensors and present usable results almost instantaneously. DARPA's "pilot's associate" program is an example of such an effort. This program fuses all sensor and C^3 inputs and provides needed information to the pilot. The development of the algorithms and associated software to make such systems useful is a significant part of this and related programs.

Data fusion programs go beyond individual platforms to more complex decision-making aids--a battlefield management system. By being able to fuse huge amounts of information, this technology can provide much more efficient tools for battle management assessment, timely decision making, rapid replanning, and survivability through distribution of tasking, machines, and data repositories. A number of such efforts are supported by DoD's Strategic Computing Program.

The Air Force's Super Cockpit program provides an example of data fusion on a vehicle platform. This program is developing ways to better present mission and aircraft status information to the pilot's eyes and ears in a three-dimensional format. It will include fusion of sensor and stored terrain information within aircraft avionics, and will eventually incorporate artificial intelligence to reduce the pilot's workload.

The Army's LHX program includes the development of both internal (system) and external (environment) status. With immediate display of the vehicle and environment (including hazards, targets), the first step in providing a decisionmaking aid will be achieved. With the addition of expert systems based on vehicle/armament performance knowledge, the vehicle commander can be provided with alternative options to cope with an array of tactical problems. Demonstrations of these capabilities for both Apache and LHX helicopters will be conducted in the mid-1990s, based on current technology base efforts.

Neural net technology is being pursued as an area of research that holds promise of simulating human learning and reasoning in combining and integrating many inputs and arriving at a conclusion likely to be correct.

Total S&T funding for this critical technology for FY 1990 is on the order of $115 million, of which about $90 million is from SDIO.

Milestones--Data Fusion

	1990	1995	2000
Model Development	• Ultra-high resolution radar signature predictions-aircraft	• Fused prediction models for multi-sensors: UV, IR, laser radar, radar, ESM, RWR	• Addition of high countermeasures environment capability
Fusion Algorithm Demonstrations	• Track file, ID, and fire control fusion-real time	• Two-dimensional radar and IR sensor data fusion using feature based algorithm	• Complete high fidelity algorithm fusion suite for ID and fire control with UV, IR, laser radar, ESM, RWR
Data Fusion Applications	• SIGINT digital data fusion systems (non-real-time)	• Pre-detection sensor integration with improved clutter suppression and low observable visibility • Real-time SIGINT processor	• Integrated sensor/ fusion processor with all signal processing done at central location for optimum suppression and low observable visibility • SIGINT expert analyst/ interpreter

D. RELATED R&D IN THE UNITED STATES

There are many similarities between the signal and data processing components of DoD's data fusion efforts and related efforts in US industry, and consequently much beneficial interaction. Specific data fusion system design, architecture, and algorithm development are unique to DoD needs.

E. COMPARISON WITH OTHER COUNTRIES

Military operations of the future will depend upon effective functional integration of multiple sensor and data sources on individual platforms and geographically dispersed and highly mobile systems on multiple platforms. Key aspects of the technology selected as indicative of significant infrastructure capabilities in data fusion are:

Accurate modeling of complex distributed systems;

Development of special algorithms for effective real-time data analysis and correlation; and

Development of high-speed (gigabit) data links.

In addition, detailed characterization and modeling of targets and sensor responses, propagation, and noise phenomena (discussed in Sections 9, Sensitive Radar, and 11, Automatic Target Recognition) will be key elements.

The table below provides a summary comparison of US and other nations for selected key aspects of the technology. Principal cooperative opportunities will exist with NATO countries, especially in technologies coming out of the ESPRIT program.

Summary Comparison--Data Fusion

	Warsaw Pact	NATO Allies	Japan	Others
Modeling of complex systems				
Algorithms for real-time analysis and correlation				
Development of gigabit/ second or faster data links				
OVERALL EVALUATION				
	Note. Despite obvious capabilities in underlying component technologies, and especially in fiber optic data links, Japan has limited experienced in practical applications of data fusion to tactical military problems.			

LEGEND:

Position of Warsaw Pact relative to the United States	Capability of allies to contribute to the technology
significant leads in some niches of technology	significantly ahead in some niches of technology
generally on a par with the United States	capable of making major contributions
generally lagging except in some areas	capable of making some contributions
lagging in all important aspects	unlikely to have any immediate contribution

Access to Japan's technology in electronics and electrooptics could clearly make significant contributions.

Virtually any nation having a well established program in information technology, such as the Alvey program in the UK or the European cooperative ESPRIT program, has the potential to contribute in a meaningful way to enhanced data fusion. Of direct application is work ongoing under these programs to develop algorithms for multi-source data fusion on massively parallel computer architectures.

For internal, or land-based systems allowing for fixed point-to-point interconnection, fiber optic communications may prove to be a key element. Here the Japanese lead offers opportunities, especially in the area of integrated optic interfaces necessary to implement high-speed data links. France (Corning) is also targeting fiber optic networks. They have reported development of a new technique for fabricating critical coupling and multiplexing components.

14. SIGNATURE CONTROL

A. SUMMARY DESCRIPTION

This critical technology makes possible the modification of the "signatures" of weapon systems, i.e., detectable characteristics by which they may be recognized, such as radar and infrared signatures of aerospace vehicles, acoustic signatures of naval ships and submarines, or the profile of a tank. The reduction of vehicle radar and infrared signatures greatly improves their survivability thus resulting in improved weapons effectiveness. The reduction of radar signature is accomplished with vehicle shaping and the use of radar absorbing materials to reduce radar echoes (mostly at microwave frequencies). The reduction of infrared signature is accomplished with cooling and the application of special materials for background matching to reduce detection by passive systems. The outline of a tank might be modified with a camouflage net or with smoke. The materials and concepts for reducing both radar and infrared signature are critical to developing weapons systems with low signatures.

A variation of this technology applied to decoys is to increase rather than reduce the signature, for example, to increase the radar cross section of a small decoy until it looks like a ship on a radar screen.

The technology (materials, structural acoustics, and fluid dynamics) to reduce hull, machinery and weapons-system noise is essential to restoring losses in and maintaining US undersea warfare superiority. Recent and continuing Soviet advances in submarine and ship quieting threaten US superiority.

B. IMPACT ON US WEAPON SYSTEMS

The reduction of radar and infrared signature of weapon systems has a broad impact on their design, support and effectiveness. The utilization of signature reduction concepts and materials can be used to improve the penetration capability of strategic systems and to improve the survivability and effectiveness of tactical systems. The use of signature reduction technology for strategic systems can render the Soviet Union early warning radar network ineffective, thus allowing penetration without weapon systems losses, and allowing penetration at higher altitudes resulting in improved capability to find and destroy targets. The reduction of the signature of tactical systems such as air-to-air interceptors and air-to-ground attack aircraft allows those aircraft to achieve higher exchange ratio and improved survivability. The reduction of both radar and infra-red signature diminishes the threat of surface-to-air missiles, thus allowing the destruction of highly protected high value targets without serious losses of aircraft.

The application of signature reduction technology will have an impact on the systems support function. The introduction of new materials as structures and coatings will require new systems support procedures. The use of signature reduction as a

capability will require special support procedures to verify the continued performance of the signature reduction techniques and methods.

Technology for acoustic signature reduction plays a major role in regaining losses in U.S. undersea warfare superiority and in widening the margin of superiority in the future. It will also enable both submarines and ships to undertake new missions.

C. PLANNED R&D

By the year 2000 advancements in radar signature reduction technology will allow the application of passive techniques to reduce the low frequency radar signature of aerospace vehicles. Techniques and materials to reduce radar signature at VHF, and generally at frequencies well below the microwave region, will reduce the effectiveness of today's Soviet early warning network.

By the year 2000 progress in the reduction of infra-red signature in both the short wave IR (SWIR) and long wave IR (LWIR) along with radar signature reduction technology will render the current Soviet Union surface-to-air and air-to-air missiles effective only at very close range.

Acoustic signature reduction is a Navy-unique critical technology being addressed by Navy programs in 6.2 and 6.3A. The technology is currently aimed at the next-generation attack submarine. Some technology base program products will be retrofitted to existing ships, submarines, and weapons before the year 2000 quiet propulsors and acoustic materials.

Funding for this critical technology comes mostly from outside the S&T program.

D. RELATED R&D IN THE UNITED STATES

These are DoD-unique technologies which are being pursued using the resources of universities, industry and other government agencies where appropriate. There are few significant commercial applications. (One example of a commercial application is the covering of structures in crowded urban environments with TV-absorbing materials to reduce TV echos; it has been used in Japan but not in the United States.)

15. COMPUTATIONAL FLUID DYNAMICS

A. SUMMARY DESCRIPTION

Computational fluid dynamics is a continuing technology development to apply the latest advances in supercomputer hardware and software to the design of improved weapons for each of the Services. This critical technology is used to increase the performance and control of aircraft, missiles, projectiles, and re-entry vehicles. In addition, there are major applications in drag reduction for ocean vehicles and in design of low Reynolds-Number folding aerostructures to provide new targeting and surveillance capabilities for forward-deployed forces. This technology is key to the development of improved solid propellant guns and superior gun-launched projectiles and missiles.

B. IMPACT ON US WEAPON SYSTEMS

Computational fluid dynamics (CFD) will lower design risks (accelerate development) and lower costs of all future Air Force flight vehicles while permitting new classes of hypersonic vehicles that currently could not even be tested. CFD is currently used to rapidly identify promising design concepts before wind tunnel tests are conducted. Current wind tunnels prohibit testing large vehicles past Mach 8. CFD will be used to test higher speed vehicles such as hypersonic interceptors, reentry vehicles, hypersonic missiles, and low cost expendable rockets. CFD is also being applied to the design of all classes of conventional aircraft and missiles to reduce drag, improve the internal aerodynamics of jet engines, improve control surface effectiveness, reduce the signature of low observable vehicles, and enhance weapons separation.

The critical enabling technologies for the NASP program are computational fluid dynamics, lightweight/high-strength/high-temperature materials and propulsion. If the maturity of these technologies allows a decision in 1990 to build the NASP X-30 research vehicle, it will be flight tested in the mid-1990s to integrate all the technologies into a flying vehicle. From the lessons of the X-30 program, follow-on vehicles that have true operational usefulness can be designed. This includes making access to space more routine and cheaper for such things as delivery of satellites to orbit. In addition, these NASP derived vehicles will be able to perform military missions within the atmosphere at greater distances and at speeds much faster than today's airplanes.

Drag reduction technology can provide ocean vehicles with much higher speeds and increased ranges with smaller power plants, using far less fuel. The goal of the drag-reduction technology program is to achieve more than a 50 percent reduction in drag through improved design achieved by application of advanced supercomputer hardware and software to computational fluid dynamics, combined with other technologies such as low-drag materials and active drag-reduction technology (heating and polymer injection). Drag-reduction can also be an undersea weapon multiplier by reducing by 50 percent the length of torpedoes which effectively doubles magazine capacity. In addition, it can provide

reduced acoustic signatures. CFD will also be used for submarine design to minimize expensive model testing and to provide the capability for quickly bringing a concept to full-scale application.

Low-Reynolds-Number Folding Aero-Structures can provide new surveillance and targeting capabilities for both surface and undersea vessels, enabling them to perform missions not now feasible and to fully support the Forward-Defense Strategy. It can also provide off-board deception and jamming to counter emerging anti-ship missile threats.

For the ground forces, longer range artillery will provide a new capability in deep attack. Higher muzzle velocities will have a major impact on antiarmor measures. Greater accuracy for gun-launched projectiles and missiles through better design is a major force multiplier.

C. PLANNED R&D

Current CFD efforts are planned to permit rapid analysis of complex aircraft configurations. Efforts continue to develop and improve methods for real and reacting gas flow fields. A moving computational grid generation method for use with existing analysis techniques will be developed for the prediction of hypersonic weapon separation and trajectory characteristics. Short Take-Off and Vertical Landing (STOVL) aircraft experience significant adverse vehicle-ground flow field interactions during thrust reversing and vectoring operations. Current test techniques cannot provide necessary details of jet and flow field interaction on the aircraft, and CFD will be used to eliminate adverse effects. However, a three-dimensional model of a jet in crossflow must first be developed.

Airframe and propulsion integration efforts are ongoing to develop high performance inlet and nozzle concepts to incorporate STOVL, high agility, and supersonic cruise capabilities into a low observable design. Design data is being developed that is critical for the integration of high performance inlets and nozzles into Mach 4 to 6 interceptor aircraft. A thorough understanding of aeroheating phenomena is required for high speed aircraft in order to build structures that can survive the extreme temperature environments. Technology programs are creating designs that minimize thermal stresses and temperature extremes. Wind tunnels are being enhanced to produce more accurate data for the validation of CFD codes. Key areas of research involve low turbulence high-Reynolds-number wind tunnels, hot wire anemometry, and laser velocimetry.

Current drag reduction work on ocean vehicles is expected to produce results which can be incorporated into an advanced technology demonstration in the 1990/95 timeframe. It is expected that this technology will be able to support engineering development of half-length torpedoes between 1995 and 2000. It is expected drag-reduction technology could be refitted to older ships by the year 2000 and incorporated in new ships beginning about 2010 when replacement of a large portion of the current fleet must be initiated.

DoD has unmanned autonomous vehicle programs which support the folding aero-structures development. This technology will transition to a joint acquisition program. Low-Reynolds-Number Folding Aero-Structures have been proposed for the Balanced Technology Initiative (BTI) and Advanced Technology Demonstrations (ATDs) which are to be completed by 1993. If program support is maintained, by the mid-1990s engineering development could be undertaken for three implementations: a submarine launched, target-

acquisition and surveillance system; an off-board deception and jamming UAVs to counter RF and IR anti-ship missiles; and a high altitude reconnaissance vehicle for long range surveillance and warning for fleet air defense.

DoD's gun-launched projectile and missile programs include studies of supersonic and hypersonic flow past finned projectiles, base flow phenomena, transonic/supersonic flow transition, and flutter divergence boundaries for supersonic missiles. In ballistics, fluid dynamics is key to the development of improved solid propellant guns. Propellants themselves are being investigated to determine optimum grain configurations based on control of propellant fracture, improved ignition systems, and associated traveling wave charge phenomena. A related part of this effort is also directed to such requirements as control of muzzle blast and flashes.

Total S&T funding for this critical technology in FY 1990 is on the order of $30 million, including both DoD and NASA.

Milestones--Computational Fluid Dynamics

	1990	1995	2000
Computational Techniques	• Rapid grid generation • 3-D Navier-Stokes codes	• Moving grid solver • Hypersonic weapons separation codes	• Real gas/ionization effects • "Inverse" methods that design rather than evaluate configuration
Hypersonic CFD	• Hypersonic missiles • Advanced reentry vehicles	• NASP • Hypersonic airbreathing missiles	• Hypersonic interceptors • Highly maneuverable reentry vehicles
Ocean Vehicles		• Half-length torpedo demonstration project	• Drag reduction applied to ocean vehicles
Low Reynolds-Number Vehicles		• Complete demonstration vehicles	• Submarine launched targeting and surveillance vehicle • Ship-launched decoy and jamming vehicles • Ship-launched high-altitude long-range reconnaissance vehicle

D. RELATED R&D IN THE UNITED STATES

While some applications such as ocean vehicle drag reduction are unique to DoD, others such as aircraft design have both military and commercial applications, and are supported by NASA and industry as well. Computational fluid dynamics programs are also extensive in DoE and many universities.

E. COMPARISON WITH OTHER COUNTRIES

Computational Fluid Dynamics (CFD) pertains to numerical methods for the solution of complex aerodynamic or hydrodynamic flow equations. Key aspects of the technology selected as indicative of significant infrastructure capabilities in computational fluid dynamics are:

Availability of advances in computational capability and in associated software engineering disciplines;

Development of algorithms, especially that required to exploit advanced computing architectures;

Development of application specific models and their underlying databases; and

Development of specialized database management software to support intensive modeling from such large empirical and experimental databases.

The table on the following page provides a summary comparison of US and other nations for selected key aspects of the technology. The United States is at present the leader in the field of Computational Fluid Dynamics. It possesses all the keystone elements and at a high level of sophistication. Cooperative opportunities will exist with NATO countries, especially in the area of specific algorithm developments. Further, if Europe proceeds with development of an aerospace plane this would provide further opportunities for cooperation.

While Japan is just beginning to undertake serious developments in CFD per se, access to Japan's computing and especially supercomputer software expertise could make significant contributions. While opportunities may be limited by trade and economic obstacles on both sides, both sides might benefit from a bilateral exchange in this area.

Secondary opportunities for cooperation in niche technologies may be realized in a number of countries, including Sweden and Israel.

The major European countries have had considerable success in the practical exploitation of Computational Fluid Dynamics. It has been used extensively in Europe to develop better designs for new transport and business jets and jet trainers. This capability for exploiting CFD is on a par with comparable methods in the United States. The European allies have both the expertise in numerical methods and the most powerful US computers.

In the area of CFD, much of the basic scientific knowledge is known to our allies. The United Kingdom is considered to have the greatest experience in applying this knowledge to weapon systems, but the FRG, Italy, and France are also assessed to have strong CFD capabilities. The ability of our allies to advance the field of CFD is expected to show a dramatic improvement during the 1990s as the number of supercomputers increases.

Knowledge of sophisticated algorithms as well as the methods for practical exploitation of CFD exist widely within NATO. France is the pioneer in finite element methods for complex aircraft configurations, England has very efficient methods for transonic flow. Germany is pioneering computations with the full Navier-Stokes

Summary Comparison--Computational Fluid Dynamics

	Warsaw Pact	NATO Allies	Japan	Others
Advanced computing capabi!ities				
Development of algorithms for advanced processors				Sweden
Application-specific models and empirically valibated databases				
Specialized database management software for large engineering databases				
OVERALL EVALUATION				Sweden

LEGEND:

Position of Warsaw Pact relative to the United States

- significant leads in some niches of technology
- generally on a par with the United States
- generally lagging except in some areas
- lagging in all important aspects

Capability of allies to contribute to the technology

- significantly ahead in some niches of technology
- capable of making major contributions
- capable of making some contributions
- unlikely to have any immediate contribution

equations. The Netherlands has an extensive effort in developing algorithms for parallel processing which also could contribute significantly.

Japan has supercomputers but does not possess the validated databases, nor does it have the sophisticated algorithms that are required. Outside of NATO and Japan most countries lack access to large supercomputers to run their computations. However, a number are involved in the development of efficient algorithms.

Sweden is involved in the development of large scale algorithms. According to some experts in CFD, the United States has greatly benefited from these developments. However, Sweden lacks the know-how on large database management and the databases themselves to be able to apply Computational Fluid Dynamics technology to state-of-the-art military problems.

Israel has been a pioneer in developing efficient multi-grid methods for a variety of flows, but is also limited by the same problems as Sweden.

China and India have shown interest in CFD, and their capability is growing. All these countries have long traditions of excellence in applied mathematics and today fully participate in the science of numerical computation methods. Some capability has also been reported in Australia, but at the present the capability level for this country is unknown.

The Soviet bloc and other potential adversaries are believed to be behind the US in this technology and are unlikely to close the gap in the foreseeable future because of US superiority in computers, software, and materials. (See discussion in Section 4.C.) However, the Soviet Union has a long tradition of excellence in mathematical numerical methods. They have been able to keep up with the United States in certain areas as in the Space program even with the serious lack of computer power. In the area of CFD the Soviets have pioneered fractional step methods. Their scientific literature seems to indicate that due to the lack of computational power, Soviet scientists and mathematicians are emphasizing efficient calculation methods. This could provide a knowledge base for development of efficient algorithms in the future.

16. AIR-BREATHING PROPULSION

A. SUMMARY DESCRIPTION

Air-breathing propulsion technology has application to a wide range of military systems, including aircraft, cruise missiles, land combat vehicles, ships, and future hypersonic systems which may evolve from the National Aerospace Plane (NASP) program. Types of propulsion systems involved include those based on diesel engines, gas-turbine engines, and ramjet engines. A broad and well balanced science and technology effort, encompassing aerothermodynamics, materials, structures, tribology, instrumentation and controls, is required to support military requirements. Within this effort, a specific example of a critical technology program, in the sense used in this report, is the Integrated High-Performance Turbine Engine Technology (IHPTET) program aimed at doubling aircraft gas-turbine propulsion system capability by the turn of the century.

A dramatic leap in aircraft propulsion capability occurred in the early 1940s with the introduction of the gas turbine engine, and substantial improvements have been made since then. Today, technological barriers in aerodynamics, materials, structural design and operating temperatures are close to being broken again, and another revolution in propulsion system performance is impending. The IHPTET initiative is guiding the development of these new technologies from the fundamental research stage, to component development, and finally to evaluation in full-scale technology demonstrator engines. These advanced technologies and components will then be ready to transition to weapon systems at far reduced risk and cost, providing vastly improved engine performance and ensuring the continued civil and military excellence of the US in aircraft gas turbine engines. The extensive high temperature materials developments which are an integral part of this program are also essential to the development of hypersonic ramjet engines, which has been greatly accelerated by the advent of the National Aerospace Plane (NASP) program.

B. IMPACT ON US WEAPON SYSTEMS

This critical technology will provide a tremendous increase in military capability and civilian productivity in the next century. Some specific goals and illustrative payoffs are given in the chart on the following page. Given that aircraft related expenditures in DoD are roughly $100 billion per year, it is clear that achieving the IHPTET goals will have a large impact on future military capability.

Some specific goals and payoffs in air breathing propulsion are given below.

Goals and Payoffs--Air Breathing Propulsion

Engine	Goals	Payoffs
Fighter	• 100 percent increase in thrust-weight ratio • 50 percent decrease in fuel consumptions	• Sustained Mach 3 + capability • Supersonic V/STOL aircraft • 100 percent increase in range/loiter/ payload over F-14
Rotorcraft	• 30 percent decrease in fuel consumption • 100 percent increase in power/weight ratio	• 100 percent increase in range/payload over CH-7
Cruise Missile	• 40 percent decrease in specific fuel consumption • 100 percent increase in thrust/unit airflow	• Intercontinental range cruise missiles in size of ALCM • High Mach capability • Low cost
Commercial/ Transport	• 30 percent decrease in fuel consumption	• Increased range/payload • Longer life, reduce life cycle costs • Reduced parts count, improved maintainability

C. PLANNED R&D

At the heart of the aeropropulsion initiative are the individual component technology programs aimed at satisfying the fundamental performance needs of the turbine engine. High pressure ratio compression systems, high temperature combustors and turbines, and lightweight structures must be achieved while maintaining or improving component efficiencies. The needed aerothermodynamic, structural, and material advances have been defined as shown in the Milestone Chart on the following page.

The aerothermodynamic, structural and material advances made in the individual component areas will be tested and verified in one of the three configurations of technology demonstrators: man-rated thrust engines, man-rated shaft power (turboshaft, turboprop) engines, and missile engines. These are also shown in the Milestone Chart on the following page.

A key to the successful achievement of the goal is the development and exploitation of advanced materials not previously available for use in turbine engines--such as carbon-carbon composites, ceramic matrix composites, metal matrix composites (MMC), high temperature alloys, aluminides, and non-structural materials for high temperature bearings and lubricants. The development of these materials for turbine engines is an integral part of this initiative and is included in the funding.

Basic research efforts sponsored by DoD and NASA at university and industry laboratories focus on the computation and measurement of fluid flow in future high-performance engines for a variety of applications, from turbine engines for the National Aerospace Plane (NASP) to more efficient diesel engines for tanks. For example, basic research programs to measure the combustion processes with advanced laser techniques (Doppler anamometer for velocity, Raman scattering for chemistry temperature, Rayleigh

Milestones--Air Breathing Propulsion

	1990 (Phase I)	1995 (Phase II)	2000 (Phase III)
Compression Systems	• Swept aerodynamics • Hollow blades • 1200°F titanium • 600°F aluminum	• 3D viscous CFD design • MMC ring rotors and spacers • 1500°F titanium • aluminide/MMC	• Max loading • Exoskeletal structure • 1800°F titanium MMC • 300°F aluminum • All composite design
Combustors/ Augmenters	• Double dome conf • Double-wall liner • Transpiration cooled augmentation liner	• Variable geometry conf • Low pattern factor CFD design • CMC augmented liner • 2000°F ceramics	• Variable flow conf • Single wall CMC liner • C/C augmentor liner • Titanium MMC cases
Turbines	• 3D, high loading • High-effectiveness cooling • Ceramic outer seals • 2100°F thermal barrier CTGS • RST superalloys	• 3D viscous CFD design • Thermal barrier coating blades • 2500°F thermal barrier CTGS • 2000°F intermetallic • 3000°F CMC • Air leak reduced 50%	• Unsteady CFD design • Exoskeletal structure • Nonmetallic disks/ blades • 2500°F niobium • 4000°F CMC • Composite cases
Nozzles	• Thrust vectoring (pitch) • Composite liners • Selective cooling • 2000°F coated C/C	• Thrust vectoring (pitch/ yaw) • Lightweight structure • Reduced cooling • 3200°F coated C/C	• Full vectoring • All composite structure • Uncooled design • 4000°F coated C/C
Controls	• VHSIC controller • Fault & battle damage tolerance • Integrated control arch	• 600-1000°F control components • Perf optimization reten • MMC components	• Integrated fiber optic system • 1200°F control components
Mechanical Systems	• 400°F liquid lube • Coated for bearings • MMC shaft • MMC accessory housing	• 700°F liquid lube • High temp ceramic bearings • Advanced dampers • Dry lube access gears	• 1500°F solid lube • Ceramic bearings • 1800°F MMC shafts • Electrical accessory drive
Tech Demo (Turbofan/ jet)	• +30% thrust/weight • +300°F max temp • +100°F comb inlet temp	• +60% thrust/weight • +600°F max temp • +300°F comb inlet temp	• +100% thrust/weight • +900°F max temp • +700°F comb inlet temp
Tech Demo (Turboshaft/ Prop)	• -20% SFC • +40% power/weight • +300°F max temp • 1000°F comb inlet temp	• -30% SFC • +80% power/weight • +600°F max temp • 1200°F comb inlet temp	• -40% SFC • +120% power/weight • +1100°F max temp • 1400°F comb inlet temp
Tech Demo (Expendable)	• -20% SFC • +35% thrust/airflow • +500°F max temp • 1100°F comb inlet temp	• -30% SFC • +70% thrust/airflow • +800°F max temp • 1200°F comb inlet temp	• -40% SFC • +100% thrust/airflow • +1400°F max temp • 1400°F comb inlet temp

scattering for density, laser-saturated fluorescence for hydroxyl radicals) are now underway.

DoD programs are closely integrated with NASA and industry programs. The funding breakdown is therefore given in the next section.

D. RELATED R&D IN THE UNITED STATES

The aircraft propulsion initiative is coordinated with NASA and with the industry R&D programs at defense contractors. For FY 1989, NASA funding for the program is $35M and industry R&D funding exceeds $150M. Together with $116M of DoD/S&T funding, the total R&D in this technology is about $300M for FY 1989. Additional research activities for hypervelocity vehicle propulsion rest principally with NASA at their Langley, Ames, and Lewis Research Centers.

Tank turbine propulsion research is coordinated with the aviation turbine initiative and directly with NASA. Diesel engine technology is coordinated with both DoE and NASA.

E. COMPARISON WITH OTHER COUNTRIES

This section addresses two areas of air-breathing propulsion, as follows:

- Advanced high temperature gas turbines for use in high performance fixed- and rotary-wing aircraft and armored land vehicles; and
- Air-breathing propulsion (supersonic combustion ramjet) for hypersonic flight.

While these are distinctly different forms of propulsion, they share fundamental underlying technologies. Key aspects of the technology selected as indicative of significant infrastructure capabilities in air-breathing propulsion are:

- Development and application of light-weight/high-temperature/high-strength materials; and
- Modeling and simulation (including as a primary subset CFD) of complex aerothermodynamic flow, and empirically calibrated data bases therefor.

The table on the following page provides a summary comparison of US and other nations for selected key aspects of the technology. Principal cooperative opportunities could exist with NATO countries, especially with France, the FRG, and the UK.

Other countries identified as having significant programs include Israel, Sweden, India, Taiwan, and the PRC. These programs are not, however, considered leading candidates to contribute to significant advances beyond existing NATO capabilities.

The S&T infrastructure for gas turbine engines within NATO is highly developed. Increasing cooperation between the European Community nations (principally the UK, France, the FRG, and Italy) in aircraft engines should permit them to field a complete range of high technology aircraft engines for military applications.

Summary Comparison--Air-Breathing Propulsion

	Warsaw Pact	NATO Allies	Japan	Others
Development and application of advanced high-temperature materials				
Modeling and simulation and empirically validated databases therefor				
OVERALL EVALUATION				

LEGEND:

Position of Warsaw Pact relative to the United States

- significant leads in some niches of technology
- generally on a par with the United States
- generally lagging except in some areas
- lagging in all important aspects

Capability of allies to contribute to the technology

- significantly ahead in some niches of technology
- capable of making major contributions
- capable of making some contributions
- unlikely to have any immediate contribution

France is also an important supplier of military and civil gas turbine engines. Their high-thrust commercial turbofan engines are based on a 50/50 joint venture with a US manufacturer. In addition, France has emerged as the leading supplier of critical ceramic composites being investigated for potential future use in jet engine hot-section development. These are being used extensively in the US IHPTET program.

A few other nations, while not a source of competitive technology for Western buyers, are successfully producing, in whole or in part, serviceable jet engines. These include the PRC and India, both of whom are successfully producing jet engines under foreign licenses.

The UK also has a sound base of ramjet experience, having fielded Sea Dart and the Bloodhound Mk2 Air Defense system, both of which use ramjets with discardable solid rocket boosters.

Outside of NATO there are reports of active programs in the PRC, Taiwan (Sky Bow), and Israel, as well as evidence of some activity in Japan and Australia.

It is important to note that there has been little foreign activity in the area of supersonic combustion ramjets, and certainly nothing comparable to the US level of activity in the National Aerospace Plane (NASP) program.

More recently, at the 1987 Paris Air Show the Soviets displayed a wind tunnel model of a Tupolev-designed Mach 5 scram-jet propelled air transport. US NASP experts have reviewed the design, which appears to be fundamentally sound.

17. HIGH POWER MICROWAVES

A. SUMMARY DESCRIPTION

High Power Microwave (HPM) technology encompasses the various technologies needed to generate, maintain, direct, and protect against microwaves produced at sufficient intensity to be used as a weapon. Critical technology contributions to HPM technology include power sources (oscillators and amplifiers: gyrotrons, backward wave oscillators, klystrons, traveling wave tubes, ubitrons, magnetrons, free electron lasers at millimeter wave frequencies, etc.), and other components and circuits for accurate pointing and tracking.

High power microwaves provide a "speed-of-light" weapon which can (a) temporarily confuse or "blind" (by jamming) electronic sensors, (b) burn them out so that they cannot function until physically replaced, (c) disable electronic control circuits (such as fuses), (d) do structural damage (e.g., set off munitions prematurely). Successful development requires advances in RF power sources, power handling, mode and frequency locking, phase control, and antenna technology. Development is also necessary to improve system ruggedness, reliability, and repetition rate.

The phenomena of atmospheric breakdown limit the amount of peak power and energy that can be concentrated on a target. This problem does not exist in space.

B. IMPACT ON US WEAPON SYSTEMS

The use of high power, directed energy weapons have multiple military applications that affect enemy weapons platforms, sensors, communications, and warheads. Because of the growing weapons system reliance on microelectronics and electrical subsystems technology by US adversaries, the HPM weapon offers a revolutionary means of defeating enemy weapons systems in mass. It also may provide means of severely interrupting enemy communications (similar to nuclear electromagnetic pulse effects) without resorting to the nuclear arsenal. Protection against such weapons in the Soviet inventory, especially laser blinding or dazzle weapons, can have an equally profound impact for US weapons platforms and sensors.

There is a corresponding need to develop protective countermeasures. In some places there is a need to protect sensitive electronic circuits from friendly high-power transmitters; it is particularly acute where there is a crowded electromagnetic environment, e.g., on board ships. Fratricide from friendly HPM systems is also a serious concern.

C. PLANNED R&D

High power microwave technology is being jointly pursued by DoD and DoE under the High Power Microwave (HPM) program. The HPM program is investigating the use of microwaves against various enemy weapons and weapons platforms. The HPM program focuses heavily on survivability, vulnerability assessment, and conceptual issues.

Total S&T funding for this critical technology in FY 1990 is on the order of $50 million.

Milestones--High Power Microwaves

	1990	1995	2000
• Test Facility in Low Microwave Region	• S-band, gigawatt power level, Bandwidth <1%	Bandwidth 10%	Bandwidth 25%
• Phased Power Sources	• PRF = 1 kHz Pulse length = 1 microsecond, Energy/pulse = 100 joules	Energy/Pulse = 1,000 joules	Energy/Pulse = 10,000 joules

D. RELATED R&D IN THE UNITED STATES

No significant commercial development of HPM technology currently exists, except that under DoD/DoE auspices. Some microwave power source R&D is carried out at universities, often in cooperation with DoD laboratories.

E. COMPARISON WITH OTHER COUNTRIES

High power microwave (HPM) is comprised of technologies for generation, controlling, and directing microwave energies of sufficient power to serve as a high-power countermeasure weapon. Key aspects of the technology selected as indicative of significant infrastructure capabilities in high power microwaves are:

> Development of microwave power components, e.g., gyrotrons, backward wave oscillators, free electron lasers, etc.;
>
> Development of power handling and control techniques for effective beam pointing and tracking.

The table on the following page provides a summary comparison of US and other nations for selected key aspects of the technology.

HPM research is also being investigated by a number of countries in conjunction with linear accelerators and for plasma heating in fusion research.

Summary Comparison--High Power Microwaves

	Warsaw Pact	NATO Allies	Japan	Others
Development of high power microwave components				
Power handling and control for beam pointing and tracking				
OVERALL EVALUATION				

LEGEND:

Position of Warsaw Pact relative to the United States	Capability of allies to contribute to the technology
significant leads in some niches of technology	significantly ahead in some niches of technology
generally on a par with the United States	capable of making major contributions
generally lagging except in some areas	capable of making some contributions
lagging in all important aspects	unlikely to have any immediate contribution

18. PULSED POWER

A. SUMMARY DESCRIPTION

Directed Energy Weapons (DEW), such as high-energy lasers or high-power microwaves, all require pulsed power modulators to turn them on repetitively for short intense bursts. The length of the burst should be shorter than the thermal time constant of the victim component, the peak power during the pulse should generate the maximum possible power in the laser or microwave beam, and the pulse repetition rate should be as high as the average available power will permit. Efficient high pulsed power sources are critical for directed energy weapons as well as other applications (e.g., radar transmitters).

Modern hypervelocity weapons such as electromagnetic and electrothermal guns and directed energy weapons such as high-power microwave sources and ground-based lasers require fieldable systems processing pulsed power levels which until recently were far beyond the state of the art. Pulsed power production is a multistep process involving energy storage, extraction, pulse generation, and modulation. Battlefield vehicles and aircraft will contain, as a prime power source, a 1,000 to 1,500 horsepower turbine which produces about 1 megawatt of continuous electrical power. The Navy's new integrated electrical drive power will provide nearly 80 megawatts of electrical power on surface ships. High power capacity batteries and high energy density capacitors are required, in tandem with the prime power sources, to provide additional energy storage, power, and pulse generation needed for a wide variety of applications.

B. IMPACT ON US WEAPON SYSTEMS

In order to effectively conduct the Battle in Central Europe, future US weapon systems must be able to markedly extend the battle space so as to successfully engage an enemy with an overwhelming advantage in force ratios. A vital need is for an extended range (3 to 5 km) antiarmor weapon which will be lethal against next generation Soviet tanks. Surface ships have an urgent need for a weapon which can intercept and destroy present and future missile systems at distances in excess of 15 km. Close air support aircraft such as the A-10 need armament capable of destroying armor on the ground at ranges of up to 5 kilometers. Great increases in weapons capability will be effected by the use of either electromagnetic or electrothermal guns. Such weapons will satisfy all of the needs delineated above.

This next generation of weapon systems will depend on the effective generation, storage, and modulation of electric power. Recent advances in capacitor and switch development over the past several years now make possible the integration and fielding of relatively compact, light-weight weapon systems on armored vehicles, ships, submarines, and aircraft in the next several years.

Ground-based directed energy weapons can also be utilized in many different war-fighting scenarios. High power microwave (HPM) sources can produce a number of "soft-kill" effects by upsetting smart electronic systems and thereby rendering ineffective such munitions as missiles and "smart" mines.

C. PLANNED R&D

Advances in high-energy density capacitors have made electric guns a viable contender for weapon systems to be fielded in less than 10 years. The DoD MILE RUN program has made good progress during the past two years. A generic 50-kilojoule capacitor with a characteristic discharge time of 10 to 100 μsec has had its mass reduced from 1,200 kilograms in 1970 to 150 kilograms in 1985 and most recently to 15 kilograms in early 1989. These units can be repetitively operated at 1 Hz and have a lifetime of nearly 10,000 shots. The mass of such a capacitor is expected to be reduced by yet another order of magnitude by 1993.

MILE RUN has also developed lower-energy density capacitors which, however, are capable of much higher repetition rate operations (up to 100 Hz) and have lifetimes in excess of 10^9 shots. These units are required to power both the SDI space-based radars and lidars and the satellites which provide the Navy's blue-green communications link. The increases in energy achieved to date and projected for MILE RUN have made available a wide variety of offensive and defensive weapon systems options which previously were considered in the "Buck Rogers" category.

The fire rates that can be sustained by electronic guns are a marked function of the battery power that will be available on the battlefield. An order of magnitude increase in battery power density from the present 1 kilowatt per kilogram to 10 times that value is urgently needed. Batteries having those power densities and also capable of storing 500 megajoules of energy in a volume of 1 cubic meter are required to permit electric gun systems to be integrated into existing battlefield and aircraft platforms. Switches, storage inductors, and other circuit elements must also concomitantly be reduced in both size and weight. High-energy, high-power switch development has kept pace and compact solid-state switches, light-weight high-energy roll gap switches, and high-power thyratrons have all made major advances.

Total S&T funding for this critical technology in FY 1990 is on the order of $65 million, most of it from SDIO.

Milestones--Pulsed Power

	1990	1995	2000
Pulsed-Power Components	• Order of magnitude mass reduction for capacitors	• An order of magnitude capacitor mass reduction	• Two orders of magnitude capacitor mass reduction

D. RELATED R&D IN THE UNITED STATES

There has been a fair amount of research by both US industry and universities in the development of HPM sources and the development of electrically driven lasers. Most of the electric gun concepts have been developed by US industry and are now being utilized by DoD. DoD-developed high energy density capacitors and associated switches have been continually commercialized over the past 10 years.

E. COMPARISON WITH OTHER COUNTRIES

Pulsed power conversion technology encompasses techniques for conversion, storage, pulse-forming, and transmission of electrical energy to power a variety of weapons (e.g., lasers, KEW, HPM, or particle beams) or high-powered radars and electronic countermeasures. Key aspects of the technology selected as indicative of significant infrastructure capabilities in pulsed power are:

- Development of reliable, high-energy density storage devices, including capacitive storage; and
- Development and use of high-speed/high-power opening or closing switches.

The table on the following page provides a summary comparison of the US and other nations in selected key areas of pulsed power. The US is the undisputed free-world leader in the development of compact, lightweight power systems for a variety of applications. Recent breakthroughs in US capacitor fabrication increasing energy densities by an order of magnitude have established a significant US lead in a key niche technology. However, the Soviet Union has an extensive program in pulse power, and may lead in a number of other areas.

Opportunities for cooperative research in pulsed power will generally be limited to NATO and Japan, and primarily in niche technologies relating to switching or know-how for specific applications. In addition, there is potential for cooperation with both NATO and Japan in a range of technologies that might be used as primary power for pulsed systems.

Summary Comparison--Pulsed Power

	Warsaw Pact	NATO Allies	Japan	Others
Development of high energy-density storage devices and systems				
High-speed switching and power control devices				
OVERALL EVALUATION	(Note 1)		(Note 2)	

Note 1. The Soviets have developed a number of alternative technological approaches. They are overall on a par with the US.

Note 2. Strong in primary power sources that may prove adaptable to pulse power applications.

LEGEND:

Position of Warsaw Pact relative to the United States

- significant leads in some niches of technology
- generally on a par with the United States
- generally lagging except in some areas
- lagging in all important aspects

Capability of allies to contribute to the technology

- significantly ahead in some niches of technology
- capable of making major contributions
- capable of making some contributions
- unlikely to have any immediate contribution

19. HYPERVELOCITY PROJECTILES

A. SUMMARY DESCRIPTION

Hypervelocity projectile technology provides the capability to propel projectiles to "greater-than-conventional" velocities (over 1.6 km/sec), as well as the unique aspects of behavior of projectiles and targets at such velocities. Propulsion systems which are being investigated include: electromagnetic guns, electro-thermal guns, travelling-charge guns with liquid or solid propellants, and hypervelocity rockets. New designs of armor-piercing rod projectiles are also being studied.

B. IMPACT ON US WEAPON SYSTEMS

The persistent numerical disadvantage in armored vehicles in Europe makes it imperative that US antiarmor weapon technology keep pace with the new generations of Soviet armor. At this time, Soviet developments such as reactive armor have made it doubtful that the current antiarmor weapon inventory will be able to defeat the threat during a Soviet blitzkrieg-style offensive.

Hypervelocity projectiles provide more penetrating and/or destructive capability. The effectiveness against simple, composite, and active armors is therefore enhanced.

The effective range of conventional unguided anti-aircraft projectiles is limited to several kilometers, since the targets can maneuver out of the line of fire during the projectile's time-of-flight. As compared to a standard gun-launched projectile, a hypervelocity projectile's time-of-flight to the target is significantly decreased, thereby increasing the weapon's effective range.

By increasing the terminal effects per unit of projectile mass, hypervelocity weapons also offer a potential reduction in the overall system's mission weight.

C. PLANNED R&D

Both electromagnetic and electro-thermal guns will require fieldable pulse power generators with power far beyond the current state-of-the-art. These were described in the critical technology "Pulsed Power" in the previous section. Efforts focused specifically on these guns include: development of materials for rails, armatures, and electrodes which resist erosion due to the intense electric arcs; designs for rail guns which are lightweight yet resist the strong electromagnetic forces; materials for rail gun armatures; and materials and designs for projectiles. Hypervelocity rocket research concentrates on propellants which meet the conflicting requirements of extremely high burning rates, low sensitivity, and low signature (flame and smoke).

The penetration capability of long-rod kinetic-energy (i.e., hypervelocity) penetrators increases with their length-to-diameter ratio (L/D) and decreases with the parasitic weight of the sabot used for launch. Therefore, research addresses our ability to produce very stiff, tough rods (which resist breakup during launch, flight, and impact), and means to keep the rod stable during launch and flight, thus reducing bending stress.

The aim of one major DoD program is to test advanced kinetic-energy projectiles in a 9 megajoule railgun; the program is carried out in accord with an MOU among the Services and DARPA. The program includes areas such as: low cost processing of ballistic ceramics; development of new alloys and processing methods for tungsten; development of light weight, high strength cermets; fundamental investigations of the physical basis of armor penetration; computational penetration mechanics and improvements in modelling high rate deformation and failure; and studies of the thermochemical processes in explosive detonation and deflagration/detonation transitions. DARPA also has a program for experimental evaluation of new armor/anti-armor technology.

DoE's role in this technology is to support DoD development of advanced conventional munitions. The President's 1985 Blue Ribbon Task Group recommended broadening the traditional mission of the DOE nuclear weapon laboratories to encompass such priority national technical problems. The Joint DoD/DoE Advanced Conventional Munitions (ACM) Program is a non-nuclear weapons technology program consisting of four related development programs. Each has as its basis a Memorandum of Understanding (MOU) between the DoE and the DoD that provides the management and procedural framework for a cooperative program of research and development (R&D) intended to improve/reduce the cost of advanced conventional munitions. The four cooperative programs are: Department of Army (DA) Cooperative Program; DoE/DoD Office of Munitions Program; Low Intensity Conflict Program; and DoD/Defense Advanced Research Projects Agency (DARPA/Department of Army/Marine Corps Armor/Antiarmor (A3) Program.

Liquid propellant gun technology demonstrations are anticipated in the early 1990s with both electromagnetic and electrothermal gun demonstrations following in the late 1990s.

Total S&T funding for this critical technology in FY 1990 is on the order of $100 million.

D. RELATED R&D IN THE UNITED STATES

Research in electromagnetic gun systems is being carried out in several independent research laboratories and universities in the United States. However, funding support comes chiefly from the government for defense applications.

E. COMPARISON WITH OTHER COUNTRIES

Hypervelocity projectile technology encompasses a wide range of techniques and materials required to obtain and maximize the effectiveness of projectiles at velocities

Milestones--Hypervelocity Projectiles

	1990	1995	2000
KINETIC ENERGY			
• Self-Forming Fragmentation Warhead	• Prototype demo	• Submunition application	
• Multimode Warhead	• 1st principles	• Prototype design	• Feasibility demo
ENHANCED BLAST			
• High Energy Insensitive High Explosives	• Formulation synthesis	• Final qualification	• Applications demo
• Reactive Elements	• Weaponization concepts	• Concept demo	• Alternate applications
• Bimetallic Warhead	• Brassboard designs	• Concept formulation	• Applications/eval
TARGET PENETRATION			
• Mobile Targets			
--Multi-Dimensional Warhead	• Feasibility demo	• Prototype warhead	• Weaponization
--Heavy Metal Warhead	• Weaponization concepts	• Concept demo	• Next generation warheads
• Fixed High-Value Targets			
--Rocket Boosted Warhead	• Full scale engineering	• Operational capability	
--Super Kinetic Energy Penetrator (SKEP)	• *Feasibility demo*	• *Prototype warhead*	• *Product improvement*
--Energy Enhanced Penetrator	• *Concepts exploitation*	• Application feasibility	• Prototype warhead
--Programmable Fuzing	• Brassboard design	• Feasibility demo	• Product improvement

greater than 1.6 km/sec. Key aspects of the technology selected as indicative of significant infrastructure capabilities in hypervelocity projectiles are:

Development of launchers and associated propulsion systems;

Development of projectiles and characterization of flight and stability; and

Impact engineering and penetrative characteristics.

The table on the following page provides a summary comparison of US and other nations capabilities in selected aspects of this technology. The United States is the leader in this technology in all critical aspects.

The Soviets are known to have a considerable interest and probably a research program in the technology of kinetic energy rounds. Data suggests that Soviet work is concentrated on the use of tungsten and tungsten alloys for kinetic energy penetrators. Their technology appears to differ from that of the US and their projectiles are employed at much greater velocities than those of the US. The differences in the Soviet technology may offer certain advantages over that of the US technology in terms of armor penetration. The

Summary Comparison--Hypervelocity Projectiles

	Warsaw Pact	NATO Allies	Japan	Others
Development of launchers and associated power systems				
Projectiles and projectile dynamics				Australia, Israel
Impact engineering and penetrative characteristics	(Note 1)			
OVERALL EVALUATION				
	Note 1. Hypervelocity > 20 km/sec			

LEGEND:

Position of Warsaw Pact relative to the United States	Capability of allies to contribute to the technology
significant leads in some niches of technology	significantly ahead in some nict.es of technology
generally on a par with the United States	capable of making major contributions
generally lagging except in some areas	capable of making some contributions
lagging in all important aspects	unlikely to have any immediate contribution

Soviets may have a technological lead over the US in developing very high power sources for electromagnetic or electrothermal guns.

20. HIGH-TEMPERATURE/HIGH-STRENGTH/ LIGHT-WEIGHT COMPOSITE MATERIALS

A. SUMMARY DESCRIPTION

Materials technology consists of an array of technologies used to produce, combine, coat, or form structures. These technologies are producing the advanced materials necessary for the design and manufacture of present and future military systems. New materials, their manufacture, and their application to and incorporation in military equipment, involve the technologies of composites, polymers, high-temperature materials, etc., as well as new manufacturing technologies for forming, fabricating, and coating, both of conventional and novel materials. Only high-performance composite thermal and structural materials and their processing are considered here. Electronic and optical materials are treated under appropriate titles.

High temperature materials technology is critical to many military and civilian applications. This technology is essentially a manufacturing technology that includes the development and production of polymeric composites, metal-matrix and ceramic-matrix composites, and carbon-carbon based materials or coatings used in high temperature environments (such as the blade of a turbine engine or the nosecone of a re-entry vehicle). Some materials, such as polymeric composites, may be applied in temperature environments less extreme than the examples cited, but still nominally "high" when compared to their traditional uses.

High-strength/light-weight materials are needed in many critical military applications. This involves technologies such as rapid solidification, epoxy-matrix, metal- and ceramic-matrix technology, advanced fiber technology, and fiber/matrix interface technologies. Coatings technology, particularly that used for corrosion resistance, are also of great importance to military applications. Some coatings are used to protect fiber/matrix chemical interactions from degrading the strength of a composite material.

B. IMPACT ON US WEAPON SYSTEMS

Composite materials technology impacts virtually every new weapon system. It is required across a wide spectrum of vehicle structures, such as high-temperature propulsion systems, hypervelocity vehicles, STOL and VTOL vehicles, as well as for spacecraft, protection against directed energy threats, and advanced hull forms and submarine structures. Next-generation materials and structures will emphasize additional multifunction capabilities where sensors and countermeasures will be integrated, resulting in options for military systems which are unheard of today. Weapons system requirements for advanced materials, both today and in the future, may be grouped around the following general characteristics:

- Damage-tolerant composite materials and hardening concepts for protection of platforms and weapons systems against operational hazards and advanced threats
- Thermostructural and electrical machinery materials for improved efficiency and reliability of advanced propulsion systems (gas turbines, air-breathing missile motors, rocket nozzles), aircraft leading edges; reentry vehicles; and electrical systems
- Submarine systems materials for improved capabilities in depth, speed and covertness, and for cost reduction
- Advanced composite materials and alloys which provide improved performance, range, and payload of vehicles and weapons systems
- Erosion/ablation resistant composite materials for all-weather capability and improved performance of missiles
- Advanced production and inspection technology for improved reliability and reduced costs of platforms, weapons systems, and facilities
- Electromagnetic absorbent materials having sufficient strength and stiffness to serve as useful structural members for aircraft, ships and missiles

Advanced materials technology offers opportunities for substantial improvements in performance and reductions in cost. The imminent demonstration of the armored-vehicle component hull will help lead to the broader adoption of components in ground and air vehicles, where weight savings of 25 to 50 percent can be achieved in the face of advanced threats. The use of adhesives can effect a 10 percent weight reduction in helicopters together with cost savings in manufacturing as a result of the reduction in processing steps. High-temperature composite materials can increase engine thrust by more than 50 percent and reduce fuel consumption by as much as 40 percent. New processing techniques can bring the costs of armor ceramics down below $10 per pound.

Advances in these areas can provide a highly leveraged means for significantly improving the operational capabilities and military effectiveness of all systems. Incremental advantages in performance or cost could, in aggregate, constitute large qualitative differences in adversary capabilities, if associated technology is systematically absorbed. Further, adversary knowledge of materials properties enhances the development of effective countermeasures and weapons against US systems.

C. PLANNED R&D

DoD's effort in high-performance structural materials technology will affect virtually all major weapons systems (the Advanced Tactical Fighter, the National Aerospace Plane, the Integrated High Performance Turbine Engine, numerous space systems, etc.).

DoD's effort in high-temperature composite structural materials will affect the development of turbine engine enhancements, space vehicle performance, and a number of other important defense systems. These efforts include development of high-temperature polymers, polymer blend composites, high-performance tribological surfaces, metal-ceramic composites, niobium intermetallics (for turbine blades), and ceramic coatings for carbon-carbon composites.

DoD's efforts in high-strength/low-weight materials include development of metal matrix composites, ceramic fiber production, and development of new high-temperature alloys through rapid solidification technology (RST). Armor technology is also being pursued aggressively by employing high-modulus fibers (for the individual soldier), ceramic-composite material combinations, electromagnetic armor, active protection armors, and modular armor.

Total S&T funding for this critical category in FY 1990 is on the order of $110 million.

Milestones--Materials and Processing

1990	1995	2000
• Assessment of new armor materials and concepts • Development of new weapons concepts • Investigation of novel, high-temperature alloys	• Development of high temperature ceramic engine components • Pervasive application of composite materials in aerospace and advanced ship hulls	• 25-50 percent weight reduction in airframes • Significant reduction in radar signature • 20-40 percent reduction in fuel consumption in many applications

D. RELATED R&D IN THE UNITED STATES

A large number of private-sector research centers are currently engaged in materials R&D. Industrial IR&D is on the order of $1 billion/year. Most major universities in the United States have significant materials research programs.

E. COMPARISON WITH OTHER COUNTRIES

This technology encompasses a wide range of techniques and material whose primary result is enhanced strength-to-weight and toughness at elevated temperatures.

Key aspects of the technology selected as indicative of significant infrastructure capabilities in composite materials are:

Ability to produce materials having specified performance characteristics; and

Development of the underlying empirical databases necessary to apply those materials to specific applications.

The table below provides a summary comparison of the US and other nations in selected key areas of materials. Both Japan and NATO have active materials development programs and may lead in selected aspects of materials research per se. The US has an overall lead, however, in the design and effective use of advanced materials in specific military applications. Primary opportunities for cooperation will occur with Japan in the

area of fibers and ceramics and with NATO in the area of ceramic composites for jet engine hot sections and, perhaps, in selected processing technologies.

Summary Comparison--High-Temperature/High-Strength/ Light-Weight Composite Materials

	Warsaw Pact	NATO Allies	Japan	Others
Ability to produce material to specified performance levels				
Development of application specific know-how				
OVERALL EVALUATION				

LEGEND:

Position of Warsaw Pact relative to the United States	Capability of allies to contribute to the technology
significant leads in some niches of technology	significantly ahead in some niches of technology
generally on a par with the United States	capable of making major contributions
generally lagging except in some areas	capable of making some contributions
lagging in all important aspects	unlikely to have any immediate contribution

The high performance materials industries have become markedly more international in character in the past several years. In collaboration with industry, governments around the world are investing large sums in multi-year programs to facilitate commercial development. Through acquisitions, joint ventures, and licensing agreements, the firms involved have become increasingly multinational, and are thereby able to obtain access to growing markets and achieve lower production costs. Critical technological advances continue to be made outside the United States, e.g., the carbon fiber technology developed in Great Britain and Japan, and hot isostatic pressing technology developed in Sweden.

The allies typically follow the US lead in the application of advanced materials to military systems. The industrially advanced West European countries and Japan have established themselves, however, as important suppliers of specialized precision machinery needed to fabricate modern weapon systems. This includes multi-dimensional weaving machines from France, hot isostatic presses from Sweden, rotary forging machines from Austria, heat treat furnaces from the FRG, and multi-axis computer-controlled machine tools from Japan and Switzerland.

The French are among the world's leaders in production of ceramic composite materials and are providing materials for the US IHPTET program. There is extensive

research activity in high temperature superalloys and structural ceramics within the European countries (including Spain and Switzerland). As in the US, there is considerable interest in attaining higher turbine inlet temperatures to increase engine performance. In addition to France, both the UK and Germany are active in the field. There is also an active research program in materials research at the Swiss Ecole Polytechnique Federale de Lausanne. The materials science department there is seen as in the mainstream of European research, drawing scientists from France, Germany, the UK, and Italy in about equal numbers. The international nature of research appears typical of much of the present materials research within NATO. These programs could be strengthened further with European unification in 1992.

This materials R&D by our allies could contribute to the US technology base, particularly the manufacturing technology base.

The Soviet Union is second only to the US and Japan in materials and structures R&D.

Thus, the US no longer has the strong lead it previously enjoyed in materials and structures technologies. There continue to be specific areas where the US is ahead, as in polymers, composites, and many aspects of automated manufacturing. However, the Soviet Union's large scale R&D effort, abundant natural resources, extensive capital investment, and support from Warsaw Pact Allies all contribute to a lessening of the leads the US had possessed and portend a growing challenge for world leadership.

Driven by the need for improved military capability, composite materials (both organic and metal matrix) are being designed into a variety of US military equipment. It is envisioned that more widespread utilization of these materials will occur in the near term. Composite materials are beginning to appear in foreign (both Free World and other) military equipment. The US is judged to have the world leadership in composite materials at the present time. This is being rapidly eroded, however, by a combination of industrial technology transfer such as is now occurring in aircraft composite technology and strong efforts by the Soviet Union.

21. SUPERCONDUCTIVITY

A. SUMMARY DESCRIPTION

Superconductivity technology encompasses both traditional metallic low-temperature superconductors (LTS) (transition temperature ≤ 23K) and the new oxide high-temperature superconductors (HTS) (transition temperature as high as 125K). Of concern are issues related to their basic properties, to their fabrication into usable configurations, and to their unique device and systems applications which capitalize on their abilities to support lossless dc currents and low-loss ac currents, to levitate, to shield magnetic and electromagnetic fields, to sense magnetic and electromagnetic fields with unmatched sensitivity, to transmit electronic signals with extremely little distortion, and to fulfill analog and digital electronics functions at speeds 10 to 20 times faster than and at power dissipation 1,000 times less than possible with semiconductors. Critical to all such applications are efficient and reliable refrigeration systems.

Large-scale LTS technology is relatively mature. Literally thousands of supermagnets are in routine use, but there has been only modest exploitation in military systems. LTS sensors and analog electronic devices are also highly developed, while LTS digital electronics systems are at an earlier stage of development, at least in the United States. LTS technology promises high utility not only in its own right, but also for pioneering systems to be executed later in HTS materials at such time as that proves feasible. HTS materials are in their infancy and are difficult to process, and so a heavy investment in R&D will be required if their apparent potential is to be realized. The course of HTS development will probably proceed from electronic transmission lines to sensors to analog and digital electronics to a variety of supermagnet applications.

B. IMPACT ON US MILITARY SYSTEMS

Superconductivity applications, some of which have already been tested in prototype form, include more compact, higher-efficiency electric drive systems for ships (and possibly land vehicles and aircraft), electric generators, electric energy storage systems for directed energy weapons, superconducting cavity particle accelerator directed energy weapons, electromagnetic guns, magnetic and electromagnetic shields, supermagnets for microwave and millimeter-wave generating tubes, magnetic and electromagnetic sensors from dc through infrared, infrared focal plane arrays, ultra-high-speed, ultra-compact signal processors and computers, high-performance low-noise communications and surveillance systems, superconducting antennas, and superconducting gyroscopes, inertial sensors, and gravimeters. In all cases the performance advantages of such systems must be adequate to more than compensate for the necessary refrigeration penalties. Many of these systems are unique with no normal-conductor counterparts, e.g., superconducting magnetic energy storage systems. In other instances new capabilities can be brought to platforms incapable of supporting conventional semiconductor counterparts, e.g., with superconducting electronics technology it should be feasible to place ultra-high-

speed supercomputing capabilities on-board aircraft and spacecraft, a capability not feasible with semiconductor technology because of its large input power requirements (200 kilowatts) and associated massive cooling system requirements.

C. PLANNED R&D

DoD superconductivity R&D programs address both LTS and HTS and cover a broad spectrum of activities extending from searches for theoretical understanding, to materials characterization, to materials processing, to invention and architecture, and finally to engineering test models and operational systems.

Total S&T funding for this critical technology in FY 1990 is on the order of $100 million.

Milestones--Superconductivity

	1990	1995	2000
Materials and Processing	• Higher transition temp. HTS materials • HTS films suitable for sensors and electronic interconnects • Theoretical understanding of HTS	• Higher transition temp. HTS materials • Quality HTS tunnel junctions • Large-area HTS films for shielding and cavity resonators	• Higher transition temp. HTS materials • Quality HTS tunnel junctions in large arrays • HTS conductors suitable for supermagnets
Sensors	• LTS sensors, dc to IR. • HTS sensors, dc	• LTS IR focal plane arrays • HTS sensors, dc to IR • LTS inertial and gyro sensors	• LTS MAD ASW systems • HTS IR focal plane arrays • HTS inertial and gyro sensors
Superconducting Electronics	• LTS analog communications and surveillance components • LTS A/D converters • LTS Nb/NbN digital electronics technology	• LTS analog communications and surveillance systems • HTS analog communications and surveillance components • HTS A/D converters • LTS Nb/NbN digital chip-level technology • HTS interconnects for semiconductor circuits • HTS digital electronics technology	• HTS analog communications and surveillance systems • LTS Nb/NbN digital signal processor and memory • HTS digital chip-level technology
Supermagnet-Based Applications	• Engineering designs for LTS rotating electrical machines for power and propulsion • Engineering design for LTS magnetic energy storage • Engineering design for LTS magnetic gun • Design study of LTS MHD ship propulsion	• Prototype LTS-rotating electrical machines • Prototype LTS magnetic energy storage system • Prototype LTS magnetic gun • Test of LTS MHD ship propulsion system • Modest-performance HTS supermagnets	• Engineering of operational LTS rotating electrical machines • Engineering of operational LTS magnetic energy storage system • Engineering of operational magnetic gun • Engineering of operational MHD ship propulsion system • High-performance HTS supermagnets
Particle Accelerators	• Tests of high frequency response of HTS materials	• Low-loss HTS cavity resonators	• Prototype HTS cavity resonator particle accelerator

D. RELATED R&D IN THE UNITED STATES

Aspects of superconductivity R&D are being actively pursued in US universities, industry, and government laboratories. Federal support is centered primarily in DoD, DoE, NSF, NASA, and DoC. DoD supermagnet-based applications may be expected to benefit significantly from the very extensive efforts at DoE on supermagnets. However, DoD interests in superconducting sensors, analog electronics, and digital electronics are being addressed only at very modest levels in other agencies and in industry. It thus appears that the US competitive position in these three very important areas will be highly reliant upon the success of DoD efforts.

E. COMPARISON WITH OTHER COUNTRIES

Superconductivity covers a spectrum of materials processing and component development techniques for both low-temperature and high-temperature superconductors (LTS and HTS). Key aspects of the technology selected as indicative of significant infrastructure capabilities in superconductivity are:

Development of HTS materials--that is, materials exhibiting superconductivity at temperatures above liquid hydrogen temperatures (i.e., around 23 K); and

Development of specific applications for LTS materials or components.

The table on the following page provides a summary comparison of US and other nations for selected key aspects of the technology. The US and Japan share a worldwide lead in this technology. Japanese technology could make significant contributions, especially in digital electronics where they enjoy a significant lead. Opportunities may, however, be limited by trade and economic obstacles on both sides. NATO research, while generally lagging that of the US and Japan, is extensive and may offer opportunities for cooperative research in a number of areas.

While overall Japan and the US are on a par, Japan has a significant lead in digital superconducting devices and systems. Unlike the US, where Josephson junction (JJ) research was all but terminated in the early 1980s, Japan has had a continued research effort in this area. Here they have apparently developed techniques to overcome the long term stability problems that caused US industry to drop its early efforts. Supported by MITI, Japan has continued to develop LTS digital logic and memory assemblies for computing applications. Component densities (20,000-30,000 JJs/1 to 4 Kbit memories) while low have been steadily increasing.

While Japan and the US are expected to remain the leaders in superconductivity, many other countries are active in the field and NATO will have significant capabilities by 1991. Europe has traditionally been strong in basic research, but has trailed in applications except in narrow niche areas such as magnets and cables. In the former, Oxford Instruments (UK) and Siemens (FRG) are leading producers of magnets for medical imaging. In addition, the CERN supercollider project is providing impetus to these areas of research.

Virtually all European nations (most notably the UK, Italy, FRG, and France) have national programs in HTS involving both government and industry. For example, Harwell Laboratory, UK Atomic Energy Authority, has established a collective search for new

Summary Comparison--Superconductivity

	Warsaw Pact	NATO Allies	Japan	Others
Development and fabrication of HTS materials				
Effective application of LTS materials	(Note 1)			
OVERALL EVALUATION	(Note 2)			

Note 1. The Soviets have developed a number of alternative techniques to circumvent specific problems. The Soviets lead the US in LTS research, development, and potential application.

Note 2. Strong in conversion and conditioning of power sources that may prove adaptable to pulse power applications.

LEGEND:

Position of Warsaw Pact relative to the United States	Capability of allies to contribute to the technology
significant leads in some niches of technology	significantly ahead in some niches of technology
generally on a par with the United States	capable of making major contributions
generally lagging except in some areas	capable of making some contributions
lagging in all important aspects	unlikely to have any immediate contribution

superconducting materials. This program is patterned after a successful program addressing electronic ceramics in the early 1980s and will involve standardized automated testing of materials. As yet, clear patterns of international cooperation at the governmental levels (comparable to JESSI or ESPRIT) have not emerged. At the research activity level, however, international ties are being forged, offering the promise of a better integrated and fruitful NATO effort in the future. For the near term, however, cooperative efforts with NATO allies will be limited to efforts wherein the US takes the technical lead, with the allied participants providing support in specific niche areas.

22. BIOTECHNOLOGY MATERIALS AND PROCESSING

A. SUMMARY DESCRIPTION

Biotechnology has emerged as a critical technology owing to the discovery and exploitation of the genetic mechanisms that control living organisms. It is now possible to engineer microbial, plant and animal cells to act as factories for the high yield synthesis of existent or de novo materials at revolutionary rates and efficiency. This technology has the potential for resolution of operational and logistical problems in the DoD in both medical and non-medical arenas. In the medical arena, biotechnology makes possible new vaccines and therapies, and in the non-medical arena it is leading to new structural materials and practical solutions to waste site remediation. Many of the products have significant civilian application and have therefore, created widespread interest. DoD has become recognized as an international leader in materials biotechnology. Continued, intense exploitation of biotechnology will provide new, more efficient and cost effective products for state-of-the-art military systems and provide a range of benefits of great economic importance. This account is therefore more comprehensive than others in this volume.

B. IMPACT ON US WEAPON SYSTEMS

It is already clear that biotechnology will emerge as the dominating force in the pharmaceutical, diagnostics and agricultural sectors of the US economy by the year 2000. The impact of biotechnology on the military capabilities of the US may be equally profound. In the non-medical arena, it will lead to the development of a vast array of products, processes and technologies including: new or improved lightweight, high strength polymers and composites for construction of aircraft, protective clothing and gear, and other military equipment; sensors for detecting chemical, biological and toxic agents; molecular switching and other microelectronic devices; bioadhesives; environmentally safe antifoulant coatings; general and specialty elastomeric compounds; high-speed specialty lubricants; and surfactants and enzymes for use in decontamination and cleaning operations.

In addition, the DoD has a significant hazardous waste problem and the enormous cost of the required remediation of 1,900 DoD sites has received a lot of recent attention. Using conventional methods could significantly impact DoD operational resources. Biotechnology offers a viable, cost effective alternative for the permanent solution of many of the DoD hazardous waste problems by using microbial or catalytic methods to degrade wastes and explosives, bioengineered polymers for radionuclide recovery, biodegradable lubricants, and anti-fouling paints.

Although medical biotechnology will not be the focus of this critical technology description, it should be noted that biotechnology will support military operations by providing new and more potent broad spectrum vaccines and therapeutics to protect against endemic and epidemic diseases encountered in deployment areas. Other products will

include preventive and casualty care pharmaceuticals such as tissue compatible adhesives and rapid wound healing promoters. The development of a low cost, artificial blood substitute is another important goal of the biotechnology program. In addition, neuroscience technology holds promise for enhanced combat performance, nerve cell repair, and immune system enhancement.

Some specific goals and payoffs anticipated from the DoD materials biotechnology initiative are given below.

Specific Goals and Payoffs--Biotechnology Materials and Processing

Goals	Payoffs
BIOSENSORS	
• Optical-based microsensors • Function-based microsensors • Biomolecular ion detector	• Improved real time detection and identification of toxics, exposives, and drugs • Improved non-acoustic undersea surveillance
BIOPROCESSES	
• Waste site bioremediation	• Low cost, permanent solution for persistent toxic substances
• Biopaintstripping	• Elimination of hazardous solvents for removal of paint from aircraft
• Enzyme decontamination and surfactants	• Enhanced decontamination and cleaning agents
• Biomining	• Enhanced recovery of strategic metals from low grade ore
• Synthesis of energetic compounds	• Lower cost and improved safety for high energy materials
BIOMATERIALS	
• Recombinant derived fibers	• Improved lightweight, high strength materials
• Biosynthetic polymers	• Low cost, low weight, high strength organic matrix composites for aircraft
• Catalytic polymers	• Self-decontaminating materials for individual and collective protection
• Bioelastomers	• Seals, gaskets, coatings with better chemical and mechanical properties
• New antifoulants	• Environmentally safe, improved performance, coatings for ships, buildings, and bulkheads
• Bioadhesives	• Unique mechanical and biocompatibility properties
• Biosynthesized lubricants	• Low cost, high performance lubricants for aircraft and missiles
• Microencapsulation	• Encapsulated, biocompatible acute care blood substitute
BIOELECTRONICS	
• Thin film, self-assembling molecular arrays and switches • Improved metallized biotubule fabrication and composites	• Increased circuit density and speed with decreased size; three-dimensional logic capability • High power microwave and energy storage devices

C. PLANNED R&D

DoD biotechnology is a multi-component program with its main goal the providing of new materials and processes in support of mission and operational requirements. A technology base has been developed for using biological systems, their paradigms and their products for application to military systems and problems. The principal areas are shown in the Milestone table and discussed below with regard to present status and future efforts required for demonstration of utility, applications ready for full-scale engineering development within the next decade and where applicable, the relationship to other related basic technology areas. The discussion below follows the topics as laid out in the table.

Biosensors--The biosensor program will develop automated sensors which will couple highly specific biomolecules for chemical recognition with fiber optic and electronic technology. The program is divided into the development of: (1) optical microsensors that detect the binding of an analyte by an antibody or receptor at the surface of a fiber optic probe and (2) systems where receptors in a synthetic lipid membrane, attached to the surface of a silicon chip, control the gating of ion channels in response to a physiologically active agent.

Bioprocessing--The bioprocessing program is based upon the remarkable ability of micro-organisms to evolve, adapt, and perform biochemical transformations over a wide range of conditions. The ability of certain organisms or enzymes derived therefrom, to perform specific chemical transformations under ambient conditions can be turned to useful advantage to produce products with unique military applications or to solve its hazardous waste and strategic metals problems. The intrinsic advantage that bioprocesses have over conventional means of achieving chemical transformations is that they are usually energetically more favorable. Consequently they are less costly, less environmentally damaging, and occur with greater speed, specificity and selectivity. Furthermore, with the advent of recombinant DNA technology, it is now possible to custom tailor organisms to perform specific tasks or to manufacture products that would otherwise be difficult or costly to obtain using conventional synthetic routes.

The primary goal of the bioremediation and hazardous waste reduction effort is to develop workable field solutions for cleaning up hazardous wastes located on military bases using a biodegradation or biotransformation approach.

Current methods of paint stripping use dangerous organic solvents or plastic media blasting which are environmentally hazardous or potentially damaging to aircraft structural integrity. A different approach that is being tested incorporates enzyme degradation. An enzymatic system does not require strict containment, can be recycled and is environmentally safe. Completed work has shown that controlled and safe biodegradation of paint is possible.

Bacterial leaching or bioleaching is a hydrometallurgical process for making metals soluble and separating them from their mineral matrices. The principal benefits of bacterial leaching are low operating costs and mitigation of air and water pollution. The current objectives are to (1) identify microorganisms which bioaccumulate strategic metals, (2) determine the mechanisms which govern the bioaccumulation or chelation processes, (3) immobilize chelators onto an inert carrier so that specific metals can be selectively recovered, and (4) suitable scale up.

The isolation, characterization and modification of enzymes, biocatalysts and surfactants for use in military decontamination operations remains a major objective of the biotechnology program. Two principal classes of contaminants are the focus of this program; (1) chemical agents (organophosphates and mustards) and (2) biological agents.

Enzymes capable of degrading both classes of agents have already been identified and partially characterized.

Biomaterials--Materials research includes chemical intermediates for synthesis of aircraft composite materials, macromolecules for the encapsulation of hemoglobulin, thin film materials for electronics, macro-molecules for the control of corrosion and fouling, self-assembling structures for microelectronics, adhesives for medical and non-medical applications, new elastomeric compounds and biomolecules for use as lubricants.

For spider and worm silks, which are fibrous biopolymers having tensile strength greater than steel and elasticity greater than wool, methods for in-vitro production have been examined and cloning of the genes responsible for the polymer have been accomplished in at least one case. Work on fiber assembly leading to scale-up is underway. In the case of elastins, polyhydroxyalkanoate elastomer strips have now been produced in small quantities. They have typical physical and mechanical properties, yet in their native form are biodegradable. Crosslinking work is being done to provide a nondegradable variety. Development of degradable and nondegradable thermoplastics using the above R&D approaches will continue. In the composite arena work has begun on identifying biosynthetic pathways for the preparation of acetylenic groups and chemical intermediates. It has been shown that these compounds can be produced using biotechnology methods and therefore, new or less costly aerospace structural composites may become available. Polypheneylene (600-700 deg. F use temperature) can be produced through microbial induced conversion of benzene (very low cost) to an intermediate. The cost is under $10 per pound compared to hundreds of dollars per pound for materials with the same thermal performance characteristics. R&D efforts will continue to identify and examine pathways from organisms which will provide chemical intermediates for use in resin matrix and carbon-carbon composites.

In the area of bioadhesives a mussel adhesive has been defined, characterized and manufactured. It forms strong, durable bonds with a variety of surfaces, cures rapidly and is nontoxic. It also has application in gluing tissues and in replacing eye lenses; the latter operation has been performed on animals. Genetic manipulation for engineering other desired material properties has been initiated for this and other bioadhesives. In the area of lubricants a material has recently been isolated from a primitive thermophilic organism which has an unusual structure and holds promise for being a cheap high temperature, chemically stable lubricant or additive. Initial wear tests and other characterization studies are underway.

In bioelectronics, DoD efforts focus on optical storage and switching devices using biomolecules and on self-assembling microstructures. All but the last are in the basic research stages. A new ultra-high resolution microlithography process, based on biomolecular R&D on biotubules, has been transitioned to industry and is the subject of a cooperative R&D agreement between an industrial concern and a DoD laboratory. The process, which will be publicly announced on 1 May 1989, has been used for prototype semiconductor devices with features less than 0.5 micron. This process promises to be technologically and economically very important to the US.

Total S&T funding for biotechnology in FY 1990 for the materials component is on the order of $40 million, and for the medical component $60 million.

Milestones--Biotechnology Materials and Processing

	1990	1995	2000
BIOSENSORS	• Dipsticks--first fielded biodetection capability	• Real-time automated CB detector for specific threats	• Receptor-based all agent generic CB detector
BIOPROCESSING			
• Bioremediation	• Restoration of soil contaminated with fuels, lubricants, & nitroaromatics	• In situ treatment of PCBs & TCEs in ground water	• End stream bioreactors using engineered organisms
• Biopaintstripping	• Degradative enzymes characterized	• Scale-up for batch processing	• Complete self-contained biostripping system
• Biomining	• Microbial strain selection	• Batch recovery of gallium from low grade ore	• Immobilized biochelators for industrial end stream recovery
• Energetics Synthesis	• Room temp synthesis of some nitrate esters & aliphatic nitro-compounds	• Full range of nitrifying & denitrifying biotech products	• Novel, high-energy propellants & explosives
BIOMATERIALS			
• Fibers	• Cloned synthesis fibers	• Solid state synthesis fiber assembly	• High strength material
• Polymers	• Intermediates identified • Cotratus identified	• Intermediate synthesis pathway cloned solid state synthesis	• Composite matrix
• Elastomers	• Producers identified • Polymer characterization • Cloned synthesis	• Production optimization • Material optimization • Solid state synthesis	• Gaskets, coatings
• Adhesives	• Cloned variants • Product variants	• Cloned synthesis • Variants synthesis	• General use adhesive • Tissues adhesive repair
• Bioelectronics	• Tubule fabrication • Fiber processing • High resolution deposition	• EMI coating & ceramics • Structural microwave composites • 0.1 micron devices	• Protected equipment • Microwave devices • 3-D circuitry
TECHNOLOGY DEMO			
• Bioremediation	• Site demo-TCE degradation	100% scale-up	--
	• Site demo-nitroaromatic compositing	100% scale-up	--
• Bioadhesives	• Binding strength demo • Eye perforation repairs	Wound repair efficacy	--

D. RELATED R&D IN THE UNITED STATES

Federal and private sector spending on biotechnology R&D exceeds $4.5B in 1987. Of this, about $2.7B was the result of Federal Investment. Most R&D within the private sector was performed in the pharmaceutical and agricultural areas. The National Institutes of Health provided 84 percent or $2.3B of the Federal spending. DoD was the second largest spender, followed by NSF, DoE, USDA, EPA, FDA and NBS Biosensors.

E. COMPARISON WITH OTHER COUNTRIES

This section encompasses a number of diverse areas of biotechnology, as follows:

Biosensors with primary emphasis on real-time detection and identification of toxic chemical/biological (CB) agents;

Bioprocessing for decontamination/remediation; and

Biomaterials covering a broad range of applications including fibers, adhesives, energetic materials, polymers, and specialized electrical and optical materials.

The table on the following page provides a summary comparison of US and other nations for selected key aspects of the technology. Because of the pervasive importance of biotechnology in health and agricultural sectors, there is virtually universal interest and activity in the field. Cooperative opportunities will exist with most of the NATO countries and many other free world nations as well.

Many European countries are active in the area and they are likely to continue developing this field rapidly. The UK, West Germany, Sweden, and the Netherlands are particularly active in biomaterials research and applications.

The West German government, for example, is subsidizing more than 40 research projects. These are all long-term, high-risk projects which it would not be possible to implement without some governmental aid. The program was begun in 1985 and, as of 1987, 16 companies in West Germany were taking part. Over $10 million was budgeted in 1987 for this program.

In the Netherlands, the founding of Groningen Biotechnology Center in 1981 combined 10 biotechnologically oriented research groups at Groningen University. Research is conducted in industrial bio-organisms, fine chemicals, industrial enzymes, and environmental biotechnology (treatment of waste).

The European organization EUREKA developed an initiative for cooperation in biotechnology. Countries working cooperatively on sponsored projects include the United Kingdom, Spain, France, and Denmark.

Many European universities and institutes are active in biotechnology. Cranfield Biotechnology Center at the Cranfield Institute of Technology is especially noted for research on biosensors. The Institute has developed rapid methods for microbial contamination monitors and provides consulting services to industry, including bioaudits to assess contamination in factory work areas.

Summary Comparison--Biotechnology Materials and Processing

	Warsaw Pact	NATO Allies	Japan	Others
Development and fabrication of real-time detection and identification of biological/chemical agents				
Bioprocessing for decontamination and remediation				
Development of biomaterials for specific applications				
OVERALL EVALUATION				Numerous Countries (Note 1)
	Note 1. Because of its pervasive importance in fundamental health and agricultural industries and the open dissemination of technology, research in biotechnology is virtually worldwide.			

LEGEND:

Position of Warsaw Pact relative to the United States	Capability of allies to contribute to the technology
significant leads in some niches of technology	significantly ahead in some niches of technology
generally on a par with the United States	capable of making major contributions
generally lagging except in some areas	capable of making some contributions
lagging in all important aspects	unlikely to have any immediate contribution

The Soviet Union has an extensive program in biotechnology research which is concentrated in a relatively small number of R&D centers located primarily in Moscow, Pushchino, Novosibirsk, and Leningrad. Although only a few Soviet researchers are believed to be performing research at the level of their counterparts in the West and Japan, others are not far behind. Moreover, in at least one important area, biotechnological research in space, the Soviets hold an advantage based on their long-term space station activity.

East Germany is emphasizing training in biotechnology at all universities, targeting interdisciplinary research and development areas; supporting collaborative projects between academic and industrial entities, expanding and updating laboratory facilities, and building new laboratories with modern equipment. East Germany's overall program is to achieve a three-fold increase in biotechnological applications by 1990.

Since much of the research in this field is published in open literature, the USSR has not faced restrictions in accessing a large body of scientific knowledge. For example, in 1982 a conference was held in Finland on the use of computers and microprocessors on process models and control of biotechnology. Topics covered included precise measurement technology and sensors, process models of bioreactors, and adaptive control in microbiological processes. Conference proceedings were published in a Russian journal of microbiology.

Moreover, the Warsaw Pact countries have been able to readily acquire Western biotechnology organisms and products. Dr. Sergey P. Sineosky, Chief of the Soviet Collection of Industrial Microorganisms at BIOGEN in Moscow, recently reported that he routinely obtained cultures from the American Type Culture Collection in Maryland, the Eschericia coli Reference Center at the University of Pennsylvania, and other Western culture collection centers. The laboratories at BIOGEN have Western biotechnology equipment, including centrifuges, chromatography equipment, spectrophotometers, culture media, automatic pipetters, HPLCs, personal computers, and scintillation counters. In the last two years the Soviets have also purchased amino acid analyzers, hollow-fiber cell culture systems, automated fermentation systems, automated DNA sequencers, and "gene machines" from Western companies.

Appendix B

CONGRESSIONAL REQUIREMENT FOR A CRITICAL TECHNOLOGIES PLAN

(Reproduced from PL 100-456, September 29, 1988)

Arms and munitions.

SEC. 823. CRITICAL TECHNOLOGIES PLAN

(a) IN GENERAL.—(1) Chapter 139 of title 10, United States Code, is amended by adding at the end the following new section:

"§ 2368. Critical technologies plan

"(a) ANNUAL PLAN.—(1) Not later than March 15 of each year, the Under Secretary of Defense for Acquisition, in consultation with the Assistant Secretary of Energy for Defense Programs, shall submit to the Committees on Armed Services of the Senate and the House of Representatives a plan for developing the 20 technologies considered by the Secretary of Defense and the Secretary of Energy to be the technologies most essential to develop in order to ensure the long-term qualitative superiority of United States weapon systems.

"(2) In selecting the technologies to be included in the plan, the Secretary of Defense and the Secretary of Energy shall consider both product technologies and process technologies.

"(3) Such plan shall be submitted in both classified and unclassified form.

"(b) CONTENT OF PLAN.—Each plan submitted under subsection (a) shall include, with respect to each technology included in the plan, the following matters:

"(1) The reasons for selecting such technology.

"(2) The milestone goals for the development of such technology.

"(3) The amounts contained in the budgets of the Department of Defense, the Department of Energy, and other departments and agencies for the support of the development of such technology for the fiscal year beginning in the year in which the plan is submitted.

"(4) A comparison of the positions of the United States and the Soviet Union in the development of such technology.

"(5) The potential contributions that the allies of the United States can make to meet the needs of the alliance for such technology.

"(6) With respect to the development of such technology, a comparison of the relative positions of the United States and other industrialized countries that are prominent in the development of such technology and the extent to which the United States should depend on other countries for the development of such technology.

"(7) The potential contributions that the private sector can be expected to make from its own resources in connection with development of civilian applications for such technology.".

(2) The table of sections at the beginning of such chapter is amended by adding at the end the following new item:

"2368. Critical technologies plan.".

(b) FIRST REPORT.—The first report under section 2368 of title 10, United States Code (as added by subsection (a)), shall be submitted in 1989.

10 USC 2368 note.

Appendix C

GLOSSARY

GLOSSARY

Ada	Name of DoD Higher-Order Language
ACM	Advanced Conventional Munitions
A/D	Analog-to-Digital
AFV	Automatic Fire Control
AI	Artificial Intelligence
ALCM	Air-Launched Cruise Missile
ALVEY	Advanced Information Technology Program (UK)
APC	Armored Personnel Carrier
ARM	Antiradiation Missile
ASIC	Application Specific Integrated Circuit
ASW	Anti-Submarine Warfare
ATA	Advanced Tactical Aircraft
ATC	Automatic Target Cueing
ATD	Advanced Technology Demonstration
ATF	Advanced Tactical Fighter
ATR	Automatic Target Recognition
AWACS	Airborne Warning and Control System
BiCMOS	Integrated Bipolar and CMOS on a Single Chip
BPS	Bits per Second
BTI	Balanced Technology Initiative
CAD	Computer-Aided Design
CB	Chemical/Biological
C/C	Carbon-Carbon
C^3I	Command, Control, Communications, and Intelligence
CBD	Chemical and Biological Defense
CCD	Camouflage, Concealment, and Deception
CFD	Computational Fluid Dynamics

CM	Countermeasure
CVD	Chemical Vapor Deposition
db	Decibel
DIA	Defense Intelligence Agency
DNA	Defense Nuclear Agency
DU	Depleted Uranium
ECCM	Electronic Counter-Countermeasures
ECM	Electronic Countermeasures
EO	Electro-Optical
EMI	Electromagnetic Interference
EML	Electromagnetic Launch
EMR	Electronic-Combat Multifunction Radar
ESM	Electronic Support Measures
ESPRIT	European Strategic Program for Research in Information Technology
EUCOM	European Command
EUREKA	European Research Koordination Agency
Europtica	European Optical Professional Society
EW	Electronic Warfare
FAE	Fuel Air Explosive
FEL	Physics and Electronics Laboratory
FLOT	Front Line of Troops
FOG-M	Fiber-Optic-Guided Missile
FOS	Fiber Optic Sensor
FRG	Federal Republic of Germany
GaAs	Gallium Arsenide
Gbit	Gigabit
GOPS	Gigaoperations per Second
HBR	High By-pass Ratio
HBT	Heterojunction Bipolar Transistor
HCT	Mercury-Cadmium-Telluride
HEMT	High Electron Mobility Transistor
HPM	High Power Microwaves

HRR	High-Range-Resolution
HTS	High Temperature Superconductor
IBC	Impurity Band Conduction
ICI	Imperial Chemical Industries
ID	Identification
IGV	Inlet Guide Vanes
IHPTET	Integrated High Performance Turbine Engine Technology
InP	Indium Phosphide
IR	Infrared
IRST	Infrared Search and Track
ISAR	Inverse Synthetic Aperture Radar
ISDN	Integrated Services Digital Network
JJ	Josephine Junction
JESSI	Joint European Submicron Silicon Program
KEW	Kinetic Energy Weapon
KGB	Soviet State Security Services
KHz	Kilohertz
km	Kilometer
kW	Kilowatts
L/D	Length-to-Diameter Ratio
LADAR	Laser Distance and Range (Laser Radar)
LCC	Life Cycle Cost
LO	Low Observable
LPI	Low Probability of Intercept
LTS	Low-Temperature Superconductor
LWIR	Long Wave Infrared
Mbps	Megabits per Second
MCC	Microelectronics and Computer Technology Corporation
MESFET	Metal Semiconductor Field Effect Transistor
MHD	Magneto Hydrodynamic
MHz	Megahertz
MIMIC	Microwave and Millimeter-Wave Monolithic Integrated Circuit
MITI	(Japanese) Ministry of International Trade and Industry

MMC	Metal Matrix Composite
MMW	Millimeter-Wave
MOS	Metal Oxide Semiconductors
MOU	Memorandum of Understanding
MTAP	Multi-Target Acquisition Processor
MW	Megawatts
NASP	National Aerospace Plane
NATO	North Atlantic Treaty Organization
NSF	National Science Foundation
NTIS	National Technical Information System
OCCAM	Programming Language developed by UK
OGV	Compressor Outlet Guide Vanes
OIP	Optical Information Processing
OITDA	Optoelectronic Industry and Technology Development Association
OS	Operating System
PRC	Peoples Republic of China
RCS	Radar Cross Section
RCV	Remotely Controlled Vehicle
RSRE	Royal Signals and Radar Establishment
RST	Rapid Solidification Technology
RWR	Radar Warning Receiver
S&T	Science and Technology
SAM	Surface-to-Air Missile
SAR	Synthetic Aperture Radar
SC	Superconductor
SEMATECH	DoD-Industry Semiconductor Manufacturing Technology (Consortium)
SFC	Specific Fuel Consumption
SHS	Self-Propagating High-Temperature Synthesis
SIMNET	Simulation Network
SLM	Spatial Light Modulator
SNPE	Societe Nationale de Propulsion et Energetiques
SOI	Silicon on Insulator
SOS	Silicon on Sapphire

SPC	Software Productivity Consortium
SQUID	Superconducting Quantum Interference Device
SRT	Strategic Relocatable Targets
STARS	Software Technology for Adaptable, Reliable Systems
STOVL	Short Take-Off and Vertical Landing
TCE	Tetrachloroethylene
TOPS	Thousand Operations per Second
TMP	Tele-Operated Mobile Platform
TNO	(page II-3)
TREE	Transient Radiation Effects in Electronics
TSMD	Time Stress Measurement Device
TWT	Traveling Wave Tube
UAV	Unmanned Aerial Vehicle
UGV	Unmanned Ground Vehicle
UK	United Kingdom
USSR	United Soviet Socialist Republics
UV	Ultraviolet
VCR	Video Cassette Recorder
VHSIC	Very High Speed Integrated Circuits
VLSI	Very Large Scale Integration
WP	Warsaw Pact
WPC	Warsaw Pact Countries
WRD&T	Weapons Research Development and Test